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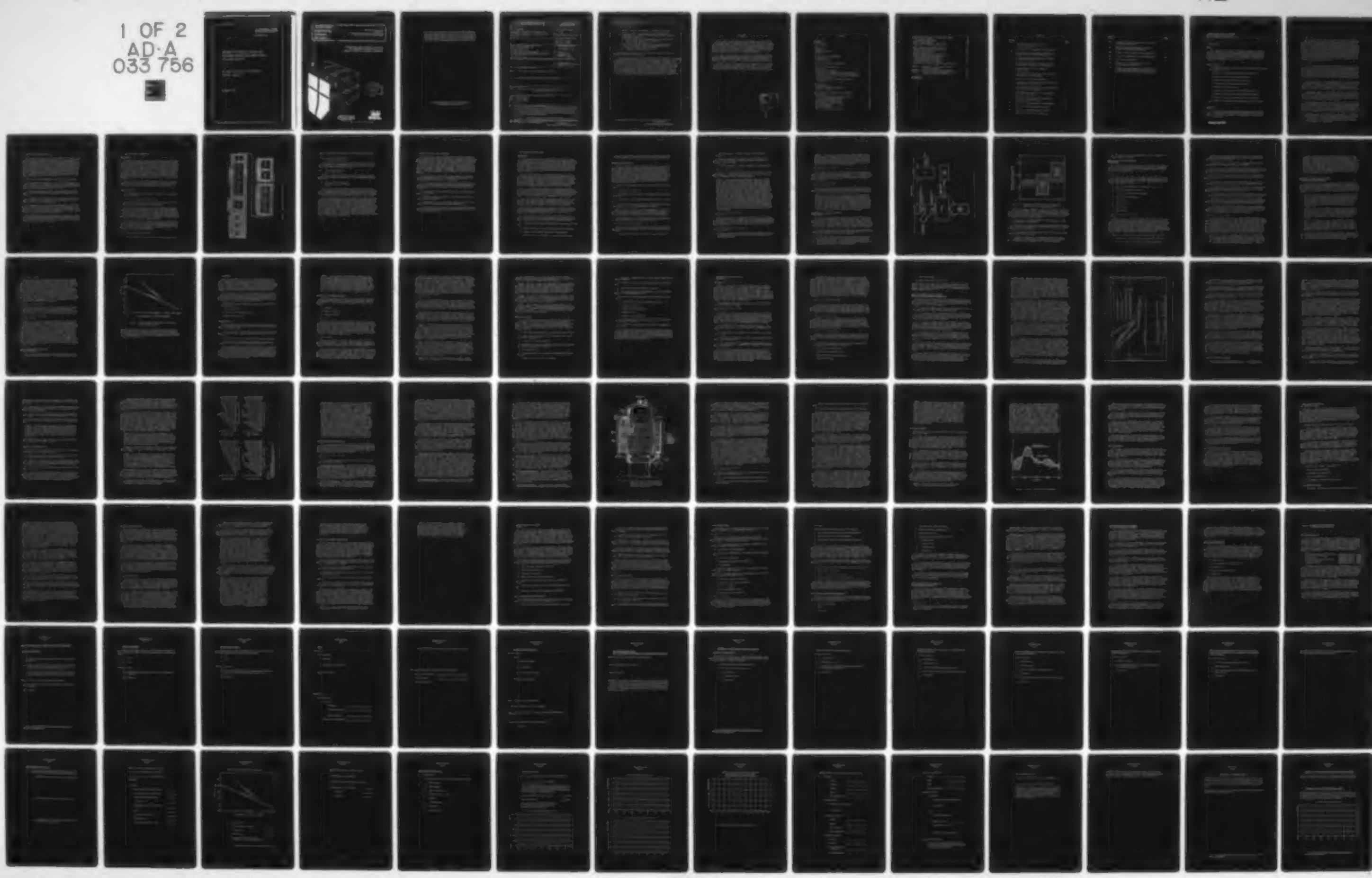

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PROCEDURES FOR FEASIBILITY ANALYSIS AND PRELIMINARY DESIGN OF TOTAL ENERGY SYSTEMS AT MILITARY FACILITIES

BOOZ-ALLEN AND HAMILTON, INCORPORATED
BETHESDA, MARYLAND

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November 1976
Development of Total Utility and Total Energy Systems
for Conservation of Resources at Army Facilities

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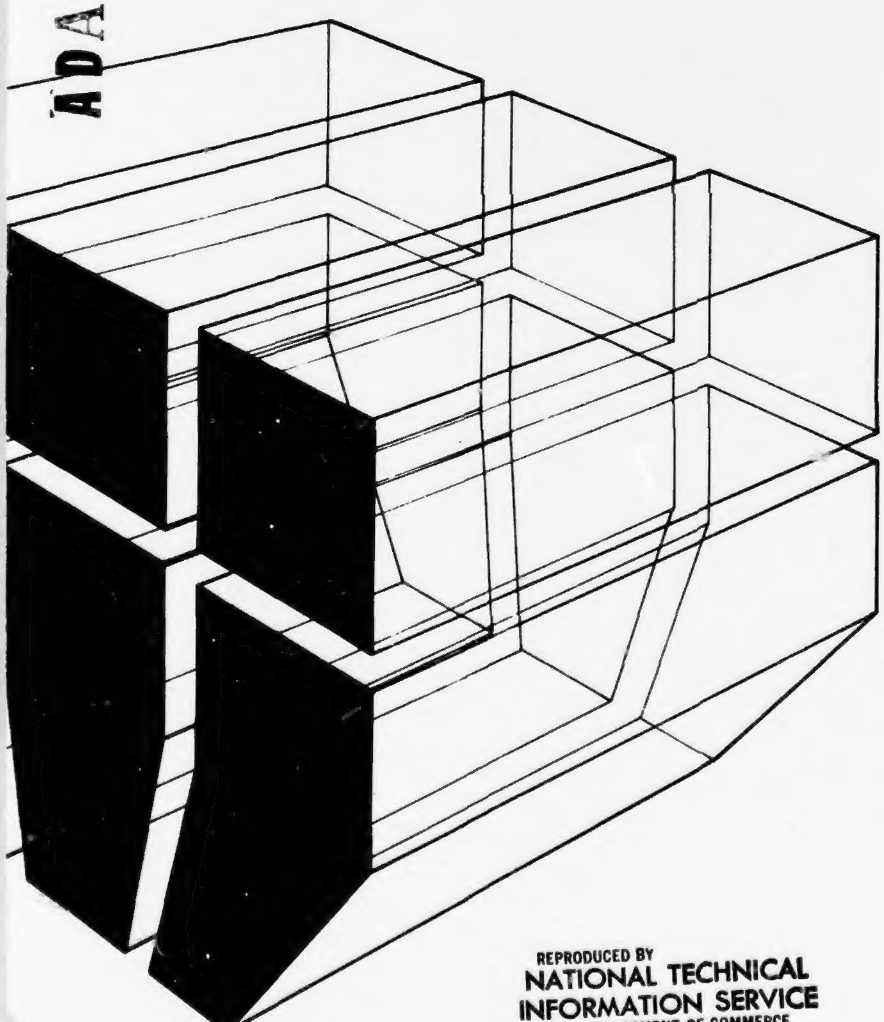

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The purpose of this manual is to provide procedural guidance and technical information for performing feasibility analyses and preliminary design of heat recovery installations, especially total energy and selective energy utility plants. This document is intended for use by facility and district engineers and for guidance of headquarters personnel.

The manual is intended for use by the Army and the Navy as an aid in performing heat recovery system feasibility analysis and for selecting and design-

Block 20 continued.

ing systems and components.

The feasibility analysis procedure is divided into five major steps:

1. Identification of gross energy requirements (Chapter 2)
2. Assessment of the viability of heat recovery within the project environment (Chapter 3)
3. Assessment of user system constraints and energy requirements
   a. Site analysis and selection (Chapter 4)
   b. Load analysis (Chapter 5)
4. Definition of candidate system configurations (Chapter 6)
5. Technical and economic evaluation of candidate systems
   a. Energy efficiency analysis (Chapter 7)
   b. Economic analysis (Chapter 8)

The engineering assessments to be carried out for completing each step are defined and explained in the manual.

The procedures described in this manual make it possible for the engineer to determine project feasibility at the earliest stage of analysis, select the best candidate systems for consideration, and complete a detailed analysis and design leading to the installation of effective heat recovery facilities. They provide a basis for selecting the best candidate heat recovery system in terms of its technical and economic feasibility. It has been assumed that users of this manual will be experienced power system designers who will insure that adequate provisions are made for system reliability, availability, and maintainability (RAM); safety; human factors; and pollution abatement in accordance with present standards governing design of military facilities.

FOREWORD

This research was performed for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under QCR 1.03.006(3), Project 4A762720A896, "Environmental Quality for Construction and Operation of Military Facilities"; Task 02, "Resource Conservation for Military Facilities"; and Work Unit 001, "Development of Total Utility and Total Energy Systems for Conservation of Resources at Army Facilities." The OCE Technical Monitor was Mr. H. Mashke, DAEN-MCE-U.

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The CERL Principal Investigator for the study was Mr. D. C. Hittle, Energy Branch (EPE), Energy and Power Division (EP). Dr. D. Leverenz is Chief of EPE and Mr. R. Donaghy is Chief of EP. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Deputy Director.

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1 INTRODUCTION

Purpose

The purpose of this manual is to provide procedural guidance and technical information for performing feasibility analyses and preliminary design of heat recovery installations, especially total energy and selective energy utility plants. This document is intended for the use of facility and district engineers and for the guidance of headquarters personnel.

Outline of Report

The aspects of feasibility analysis and preliminary design covered in this document include:

1. Selection of optimum sites for system installation
2. Methods for establishing load requirements
3. Information required for system definition
4. Procedures for defining candidate systems
5. Equipment selection criteria
6. System sizing, reliability, and redundance criteria
7. Methods for predicting system technical performance
8. Methods for performing comparative economic analysis
9. Methods for determining optimum technical and cost performance.

Background

The following information relating to government policy, definitions, and the general advantages and shortcomings of heat recovery systems is offered as background to the development of the feasibility analysis procedures.

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Government Policy

The DOD Construction Criteria Manual (4270.1-M) was modified on 24 September 1974 by the addition of subparagraphs 10.3.1C, D, and E to require that an engineering study be made of the feasibility of using a total energy system, a selective energy system, or prime mover driven heat pumps in all new construction or in the rehabilitation of buildings or building complexes in certain categories of building type and project cost. DOD 4270.1-M and related military policy directives should be reviewed in detail at the outset of all major construction or rehabilitation projects dealing with energy-consuming structures. Project cost and other criteria for determining whether feasibility analyses should be conducted will vary with time; therefore, the most recent direction should be followed.

Definitions

If the heat rejected from prime movers can be recovered and used, the overall fuel utilization efficiency can be improved considerably. Many equipment configurations for exploiting this method of energy conservation are practical. The following terminology for distinguishing the major types of heat recovery systems is taken from DAEN-MCE-U's "Engineering Instructions for Preparation of Feasibility Studies for Total Energy, Selective Energy and Heat Pump Systems" dated 1 July 1975.

Conventional System. A conventional system is any typical energy system employed on military installations which uses commercial electrical power and generates steam or hot water in a central or self-contained energy plant. Chilled water for air conditioning may be generated in a central plant and/or decentralized in various buildings.

Total Energy System. A total energy system is a concept of an on-site electrical power-generating system arranged for maximum use of input fuel energy by using the waste heat for space heating, space cooling, and domestic water heating. Generally, a total energy system is completely independent of commercial power.

Selective Energy System. A selective energy system is a concept where part (generally 40 percent to 70 percent) of the required electrical power is generated on site by a generating system arranged for maximum use of input fuel energy by using the waste heat for space heating, space cooling, and domestic water heating. The balance of the electrical power requirements is obtained from commercial sources.

Heat Pump System. A heat pump system concept is a modified air conditioning system in which the refrigeration equipment is arranged in such a manner that it can be used either to cool, heat or do both simultaneously. The refrigeration compressor may be driven by an electric motor or by a prime mover.

Advantages and Disadvantages of On-Site Power Production With Heat Recovery

On-site power production with heat recovery has a singular significant advantage over conventional utilities: energy conservation. Considering production of both shaft work and heat, total energy and selective energy plants have a practical maximum fuel energy utilization of approximately 80 percent. A direct comparison of this value with the efficiency of conventional utilities cannot be performed without reference to a particular application, but as much as a 20 to 40 percent reduction of overall energy consumption is possible when total or selective energy plants with waste heat recovery are used; however, each application must be studied and compared with conventional systems.

The most significant drawbacks of heat recovery systems are:

1. Higher capital investment. If no significant amount of installed equipment is available for conversion to a heat recovery mode, an on-site heat recovery utilities plant will require a larger initial investment than conventional utilities services.

2. Increased operational burden. The generation of utilities on-base incurs an increased operational burden of maintenance and staffing.

3. Greater criticality of operation. The interrelation of heat production with electrical generation increases the level of skill needed to operate a heat recovery system.

4. Requirement for fixed ratios of thermal energy to mechanical energy. The amount of heat recoverable from most prime movers is a fixed function of the prime mover's thermodynamic characteristics and shaft load. If recovered heat cannot be fully used or stored, the maximum efficiency of the plant cannot be achieved.

The tradeoff between the advantages and disadvantages of heat recovery must be made in the context of the specific application. The following chapters show how the context of the application is defined and how the actual tradeoff is performed.

2 FEASIBILITY ANALYSIS PROCEDURE

Introduction

The following chapters provide a detailed procedure for performing the selection and feasibility analysis of heat recovery systems (see Figure 1). The chapters are keyed to this diagram, as indicated by the chapter numbers shown in individual blocks or groups of blocks within the steps. The procedure is arranged so that detailed technical analyses are performed at the end. This insures early recognition of a proposed system's lack of feasibility, thus preventing useless expenditure of effort for detailed technical and economic analysis. This manual presents the steps of the analysis in sequence, so that background information required for every step will already have been developed.

Appendix A is a checklist and computation guide for performing feasibility analyses of heat recovery systems. The format of this checklist follows stepwise the procedural discussion of the text.

Procedural Outline

The feasibility analysis procedure of Figure 1 can be subdivided into five major steps:

Step 1: Identify Gross Energy Requirements

Assess whether electrical and thermal energy demand will justify installation of a total energy/total utility plant.

The first step may be followed in two different ways, depending on the purpose of the feasibility study. The study may be conducted in response to a general directive to examine total energy/selective energy systems as utilities service for another construction project; or it may be conducted to examine the feasibility of installing a heat recovery utilities plant explicitly for the purpose of energy conservation, without being related to other construction.

If the study purpose is to examine total energy/selective energy systems as the utilities source for another construction project, the project identification will be implicit in the project specification. Energy consumers and energy requirements are usually described in the project specification design documents.

Step 2: Conduct Preliminary Analysis of Heat Recovery for the Site

Conduct a preliminary analysis using factors discussed in Chapter

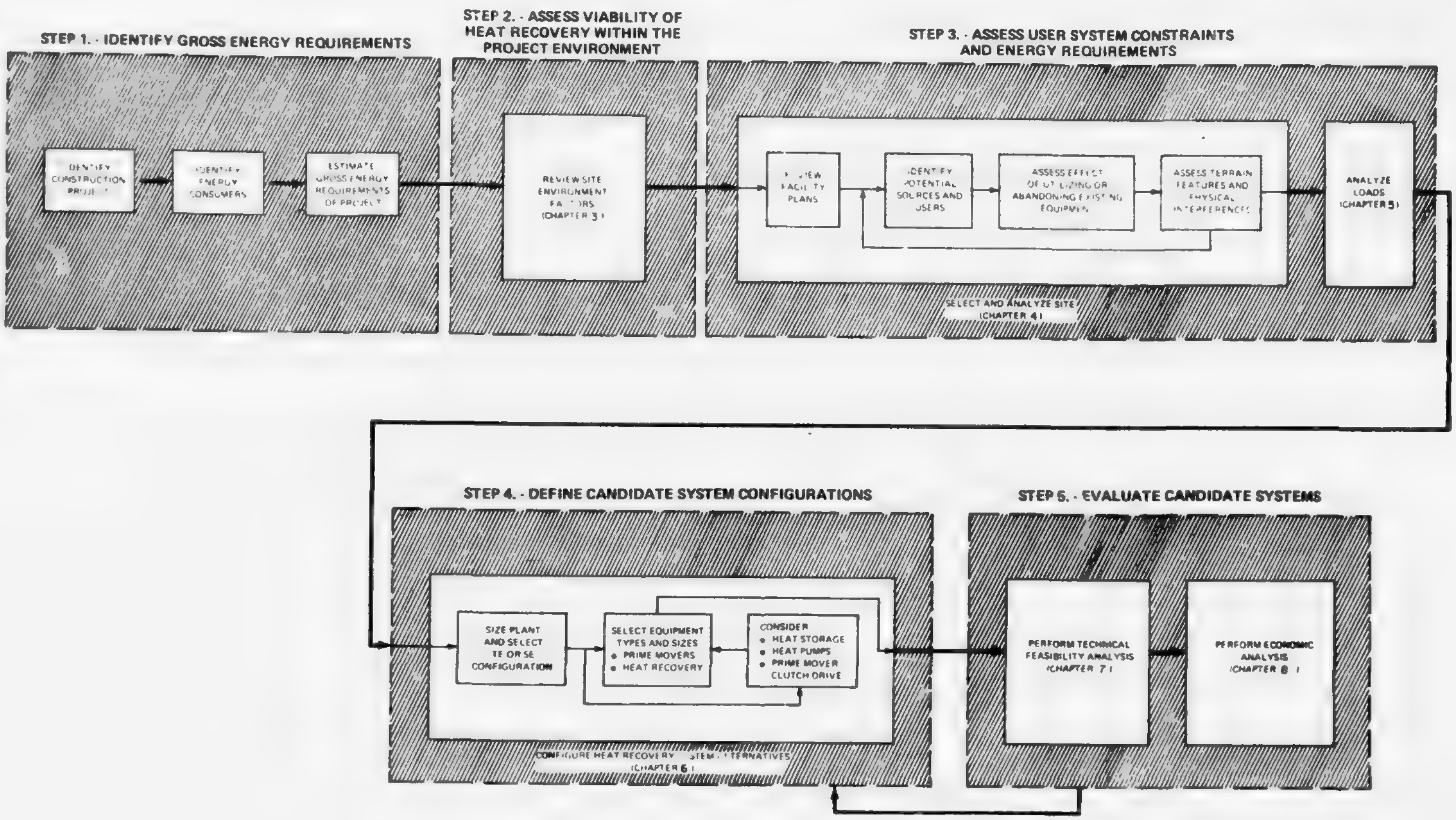


Figure 1. Heat recovery system feasibility analysis procedure.

3 prior to performing detailed site analysis and extensive calculations.

Step 3: Analyze User System Needs and Energy Requirements

Investigate user system needs, taking into account overall plans for the facility, existing equipment, and plant location. Compute energy requirements for the user system.

Step 4: Develop Heat Recovery System Alternatives

Develop a number of heat recovery system alternatives based on energy loads and operating conditions. Follow procedures presented in Chapter 6.

Step 5: Analyze System Alternatives and Select the Most Suitable System

Analyze system alternatives based on energy use, life-cycle cost, first cost, and operational problems. Compare system alternatives and select or recommend system(s) most suitable for the site. Technical and economic evaluations are described in Chapters 7 and 8, respectively.

Although the analytical process has been divided into these broad steps, which are subdivided into more specific steps within the individual chapters, the engineer using this procedure should develop the ability to view the analysis as a whole. Figure 1 indicates major areas where steps may require iteration or where information developed at one point in the analysis may modify results developed at an earlier point. The engineer should be able to recognize other interactions between procedural steps. The procedure presented here should be used as an aid rather than as a constraint, and in all cases, sound engineering judgment should be the principal guide to the means of conducting an analysis and weighing the results.

3 REVIEW OF POTENTIAL SITE ENVIRONMENT

This chapter describes the approach to be followed in Step 2 of Figure 1 and discusses factors that should be reviewed to determine the acceptability and viability of a heat recovery plant within the locale of the proposed site. In most cases, a firm decision to proceed with a heat recovery installation cannot be made at this stage; some factors (such as rates for purchased utilities) must continue to be considered in subsequent stages of the analysis. Caution should be exercised to insure that a judgment of the general feasibility of heat recovery is not made prematurely. The following are the factors to be considered:

1. Advantages of on-site power production with heat recovery in the intended application (i.e., is the project large enough; is on-site generation required, such as in a hospital)

2. Fuel availability and cost (What are the rates, terms, and deviation of fuel supply contracted; are any sources provided on an interruptible basis? Will a new generating plant on post affect rate structures?)

3. Environmental impact (Review emission and noise standard and water availability)

4. Operator personnel availability (Are qualified post or contractor personnel available?)

5. Competing electric utilities (Are there any laws or "goodwill" relationships that influence on-site power production?)

6. Existing on-site utilities (Is the proposed plant consistent with existing and planned utility distribution systems? Does it "fit in" to the post master plan?)

4 SITE ANALYSIS AND SELECTION

Introduction

An extensive site analysis is required for a prospective heat recovery system because its installation, unlike that of most construction projects, requires examination of the project neighborhood as well as of the project itself. To achieve load characteristics that will optimize feasibility of the energy sources, establishing the optimum site for a heat recovery system may require the exploitation of heat sources and heat users besides those that are part of the basic construction project.

During a large fraction of the yearly operating cycle, the site for a heat recovery system must provide a balance between the prime mover shaft load (most commonly electrical generation) and the thermal load. Primary emphasis should be on insuring the use of a maximum amount of waste heat. Production of less waste heat than is needed by the thermal load is usually only a minor problem, because additional heat can be produced efficiently and economically with boilers.

In a construction project where heat recovery may be used as an energy source, an investigation should first be made to determine where any prime movers exist in the vicinity of the project which might serve as reliable sources of waste heat, either in their present operating mode or in an altered operating mode required for heat recovery.

Unless the construction project immediately proves to be an ideal load for a heat recovery system, consideration should be given to combining other potential loads in the vicinity with the construction project, so that the combination will improve the load balance.

The procedures for selecting and analyzing a potential site for a heat recovery system through an assessment of user system constraints and energy requirements are defined in the first part of Step 3 of Figure 1 and include the following steps:

1. Review facility plans for construction, maintenance, and utilization of structures, so that the installation of a heat recovery system will be compatible with other present and planned activities

2. Identify potential waste heat sources and users in the relevant locale

3. Assess the effect of using or abandoning existing equipment

4. Assess terrain features and physical interferences.

If several sites or a combination of sites are being considered,

site analysis may become an iterative process, as indicated in Figure 1, until the optimum site for a heat recovery system is identified.

Review of Facility Plans

A review of facility plans is necessary, because installation of a heat recovery system will generally impact other base utilities; these impacts should be identified and assessed for each potential heat recovery installation. Furthermore, an attempt should be made to integrate the installation of a heat recovery system into the overall construction and energy conservation plans of the facilities. Plans to be reviewed will include construction utilization of structures, demolition and abandonment of structures, and expenditures for existing on-base utilities, emergency standby power, and other energy conservation projects.

Sources for information relating to the plans of the facility include:

1. The facility master plan

2. The current list of requested and approved facility construction projects

3. The staffs of tenant commands occupying the facility's structures

4. Facility, district/field division, and headquarters offices responsible for facility energy conservation projects.

Facility plans are subject to frequent change due to changes in military posture and project funding. A potential heat recovery installation should be configured so that a change in the facility's plan is not likely to alter the feasibility of the installation.

The following aspects of facility planning should be considered when analyzing the site for a heat recovery system:

Present Use of Individual Structures

Factors of present use that relate to the electrical and thermal load characteristics of potential structures should be considered, including:

1. Purpose of structure (e.g., barracks, school, mess hall)

2. Occupancy profile, in terms of number of occupants by time of day

3. Type of occupants (for example, a barracks occupied by recruits will have a different lighting profile than a barracks occupied by senior personnel)

4. Installed equipment, by energy consumption and usage profile.

Future Use of Individual Structures

A change in a structure's use may cause a major change in its load characteristics. Unless continued current use is evident, future use should be determined from the responsible agency.

> EXAMPLE. A large office-type structure has been used as an administrative center for a military service. When the original tenant command vacated the building, plans were made to convert the building for use as a basic electronics training building. The conversion would have greatly increased the occupant density, involved the modification of interior partitions, extended the daily occupancy of the building (two training shifts per day were expected), and included the installation of extensive energy-consuming electronic equipment. The existing space conditioning equipment was rendered inadequate for the intended future use, and a heat recovery plant was therefore analyzed as a utilities source for a new occupant configuration. The heat recovery installation proved feasible, but before the expected configuration came into effect, the building's occupancy plans were changed again, rendering the use of the building beyond a 2-year period indefinite. Based on this uncertainty and on other changes to a related construction project, plans for the original heat recovery system had to be abandoned.

Plans for Construction, Demolition, and Abandonment

Potential heat recovery systems that will serve a region around a facility should be viewed in terms of plans for construction, demolition, and abandonment of structures within that region. Potential changes in plans due to such factors as budget and military posture changes should also be considered.

Plans for Modifications and Maintenance of On-Base Utilities

Planned expenditures for modification and maintenance of existing on-base utilities systems may affect the feasibility of a proposed potential heat recovery system.

EXAMPLE. If steam lines serving an area of a base have seriously deteriorated, the installation of a heat recovery system may eliminate the need for replacement of the original lines. While the heat recovery system itself may require distribution piping, the elimination of major steam line repairs will significantly reduce the differential capital cost of the new system.

Plans for Emergency or Standby Power Requirements

Certain types of facilities, such as hospitals and communications stations, require emergency or standby generators. If an emergency power source is planned for a facility, the possibility of substituting a continuous-duty heat recovery system for the conventional standby units should be assessed.

Impact on Other Planned Energy Conservation Projects

Since energy conservation is a principal motivation for most heat recovery installations, potential heat recovery systems that will coincide with other planned energy-conservative projects should be assessed.

EXAMPLE. A large hospital is considered as a site for heat recovery utilities. Also, a major modification to the ventilation system of the hospital is being studied to reduce the makeup air requirement from its present value of 100 percent to a much smaller fractional value through the use of newly approved air filtration systems. Since the ventilation load is presently the largest component of the overall thermal load, the modification to the ventilation system should be considered as a major factor when assessing the hospital as a site for the heat recovery plant.

Identification of Potential Sources of Waste Heat

All potential sources of waste heat within an area should be examined when assessing potential heat recovery system sites. Generally, any engine will reject a major part of its input energy as heat and should be examined as a candidate for heat recovery. (The applicability of specific engine types is covered in Chapter 6.) Providing the following services may offer an opportunity to use engines suitable for heat recovery:

1. Electrical power generation. Total energy and selective energy plants should be considered as possibilities for providing all or part of the electrical load of a facility or its subareas.

2. Other shaft power applications. Consideration should be given to direct prime mover drive of large compressors, centrifugal chillers, process pumps, and heat pumps. The use of heat recovery with direct prime mover drive greatly expands the feasibility envelope of a potential heat pump installation as indicated in Figures 2a and 2b.

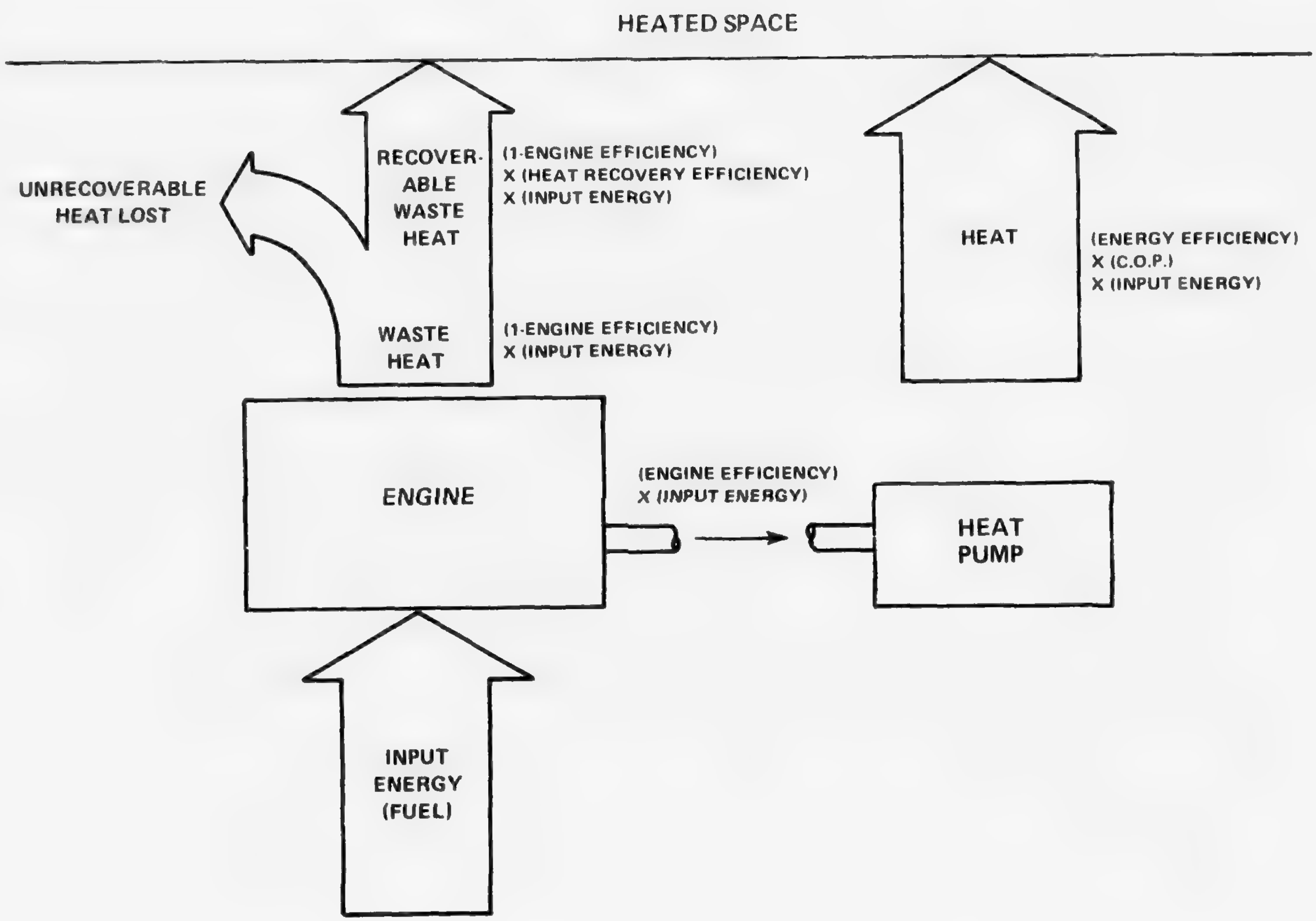


Figure 2a. Heat flow for prime mover--driven heat pump.

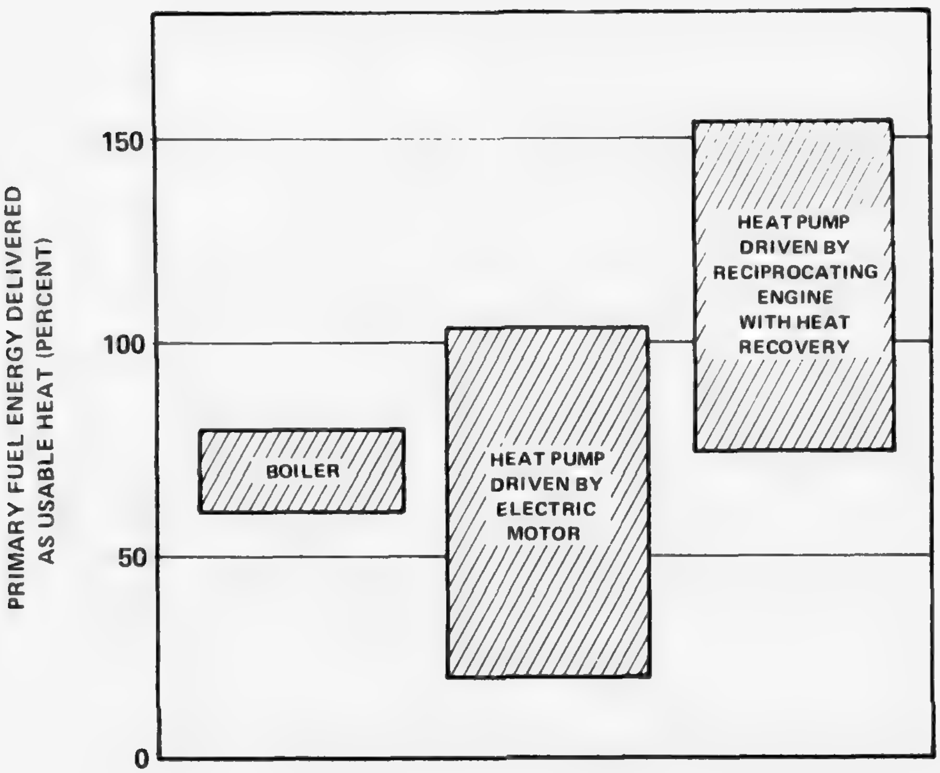


Figure 2b. Comparative efficiency ranges of heat pumps, electric motor, and prime mover drives.

Existing prime movers should be examined as candidates for heat recovery, and those on intermittent or standby electrical generating service should be considered for conversion to continuous duty. The following factors should be included when assessing the possible conversion of a prime mover to a heat recovery system:

1. The value of existing equipment should be treated as a sunk cost in considering its conversion.

2. The effect of operating heat recovery equipment on the operational characteristics and reliability of prime movers should be considered for each mode of heat recovery.

3. The suitability of the equipment for operation under extended schedules should be investigated.

4. Changes in staffing or in the required proficiency levels of present operators and maintenance personnel and the availability of additional personnel with adequate skills should be evaluated.

5. The condition of ancillary equipment, such as steam and condensate lines, should be examined.

Identification of Potential Users of Waste Heat

The vicinity of the proposed construction site should be examined to identify all significant potential users of waste heat. The thermal characteristics of these loads should be determined, both individually and in suitable combinations.

Applications

Any application where fuel is expended to provide heat is a candidate for waste heat utilization if the temperature and quantity of recoverable heat are compatible with the need. Demonstrated applications of waste heat recovery include:

1. Space heating with heated air, hot water, or steam
2. Cooling with absorption chillers
3. Domestic hot water, including laundry
4. Cooking with steam kettles
5. Sterilizing
6. Combined cycles
7. Desalination
8. Snow melting.

Load Characteristics of Individual Facilities

The energy consumption characteristics of an energy user are the factors that determine the technical suitability of a site for exploiting heat recovery. Detailed energy consumption characteristics can be ascertained only by detailed load analysis (discussed below) or, in unusual cases, by instrumentation which has been installed and monitored for a full operational cycle (a year, in the case of space conditioning equipment). However, general energy consumption characteristics can be judged from the type of structure and from examination of its use.

Generally, the conditions sought in a heat recovery load are:

1. A high ratio of thermal energy use, to achieve fuel efficiency
2. Continuous loads, to achieve rapid payout of equipment.

The degree to which these conditions are met in individual facilities can be estimated reasonably well by examining the following qualitative features of potential sites:

1. Peak mechanical or electrical load: estimated from common design guidelines or from demand metering, if installed.

2. Peak thermal load: estimated from the heated and cooled volume of the space, the type of construction, the nature of the internal thermal loads, and the typical diversity factor for the building usage.

3. Daily mechanical/electrical load profiles: estimated from the usage of the structure. Typical profiles can be measured if metering is installed.

4. Daily thermal load profile: estimated from the usage of the structure, typical daily temperature variations, and temperature setbacks.

5. Seasonal mechanical or electrical load profile: should be investigated to determine variations with changes in seasons or with other yearly cycles, such as school training sessions.

6. Seasonal thermal load profile: can be estimated from fuel consumption or steam demand (if these are metered) or from standard load factors.

7. Availability of flexible thermal loads: should be examined to determine whether the load has components whose consumption can be scheduled at will. Examples of such loads include desalination and water heating.

8. Relation to electrical grid load profile: should be examined in the case of potential selective energy systems to determine whether the electrical load characteristics of the facility served by the heat recovery plant are complementary to the network load profile.

Combination of Facility Loads

An individual user facility may not always maintain adequately high usage of plant equipment or offer sufficiently balanced shaft and thermal loads. Significant improvement in load characteristics can often be made by combining the load of a facility with the loads of one or more facilities of different types. The characteristic sought is a balancing of both shaft and thermal loads between different facilities, so that both load balance and the total load are kept as constant as possible. An advantage of load combinations is that shaft and heat loads do not have to be balanced in individual facilities, but only in the total load.

> EXAMPLE. In a complex of buildings consisting of classroom buildings, barracks, and a recreation building, the electrical load will tend to follow occupancy from one building to another. During weekdays, the load will be the highest in the classroom building, shifting to the barracks during morning and evening hours. In the late

evening and on weekends the recreational facility will pick up electrical load, and there will be a reduced consumption in the barracks. The thermal load will shift in winter from the classrooms by day to the barracks and recreation facility by night and on weekends. In summer, the thermal load will be concentrated in the classroom building by day, and in the recreation facility during late evenings and weekends. Thus, the load factor of the heat recovery plant is kept high during about two-thirds of its operating hours, and the balance between the electrical and thermal loads will be favorable most of the time.

Assessment of the Effect of Utilizing or Abandoning Existing Equipment

The condition of existing equipment which could be incorporated into a heat recovery system should be determined. It should also be determined whether existing equipment would be required to operate under altered operating conditions as part of a heat recovery system, and if so, whether the equipment will function properly under the altered conditions.

EXAMPLE. Steam lines currently used to distribute high-pressure steam from central steam plants may be located suitably for use in distributing low-pressure steam from a heat recovery plant. However, steam and condensate lines are frequently in a condition inadequate for use with a heat recovery system. Also, high-pressure lines may be too small to transmit the lower pressure steam.

EXAMPLE. Existing heating fixtures in buildings are designed to operate within a certain range of temperatures and temperature differentials. It should be determined whether the existing heaters can operate at sufficient capacity with steam or hot water at the temperatures supplied by a heat recovery system.

EXAMPLE. A compressor currently being used only for summertime cooling may have the proper capacity for use as a heat pump in a heat recovery system. However, it should first be determined whether the compressor will operate satisfactorily under the much longer cycles and possibly different pressures necessary in heat pump service.

Reciprocating engines require especially critical examination before determining their suitability for conversion to sources of waste heat. The following aspects of engine performance should be considered when assessing the suitability of existing engines:

Load and Service Ratings

A large proportion of presently installed reciprocating engines were originally intended for emergency or standby service. Whether such engines are suitable for the continuous duty of a heat recovery plant is largely a function of their power output in relation to speed. Figure 3 gives generally acceptable limits for the operation of a diesel engine in standby duty and in long-running, continuous duty. Frequently, engines on standby or emergency service will fall within the performance envelope for continuous duty, but this should be verified in each case. It may also be feasible to derate an engine for continuous duty. Figure 3 indicates that much less derating is necessary to bring an engine within the continuous duty envelope if a reduction in speed can be made; however, this is not possible with engine generators unless the generator is changed.

Engine Thermal Characteristics

It should be determined whether an existing engine has the proper thermal characteristics for use in the heat recovery applications being considered. Chapter 6 and Appendix B discuss the thermal characteristics of engines with respect to different modes of heat recovery.

Jacket Heat Recovery at Elevated Jacket Temperatures

Converting an engine to operate with higher jacket temperatures is not routine, and should be performed only with detailed guidance from the engine manufacturer. Following manufacturer guidance is particularly important when attempting a conversion to ebullient cooling, in which the engine is used as a boiler. In engines employing ebullient cooling, the block, cylinder heads, and any external exhaust passages through which coolant flows must be designed to prevent entrapment of static pockets of steam within the engine. Such design must be verified before attempting conversion. If conversion is advisable, the most common modifications required are replacement of conventional cylinder and water pump seals with seals resistant to the higher jacket temperatures employed. Modification of cylinder seals requires removal of the cylinder liners, a task equivalent in magnitude to a major overhaul.

Assessment of Terrain Features and Physical Interferences

For each configuration and combination of structures which may become part of a heat recovery system, an assessment should be made to

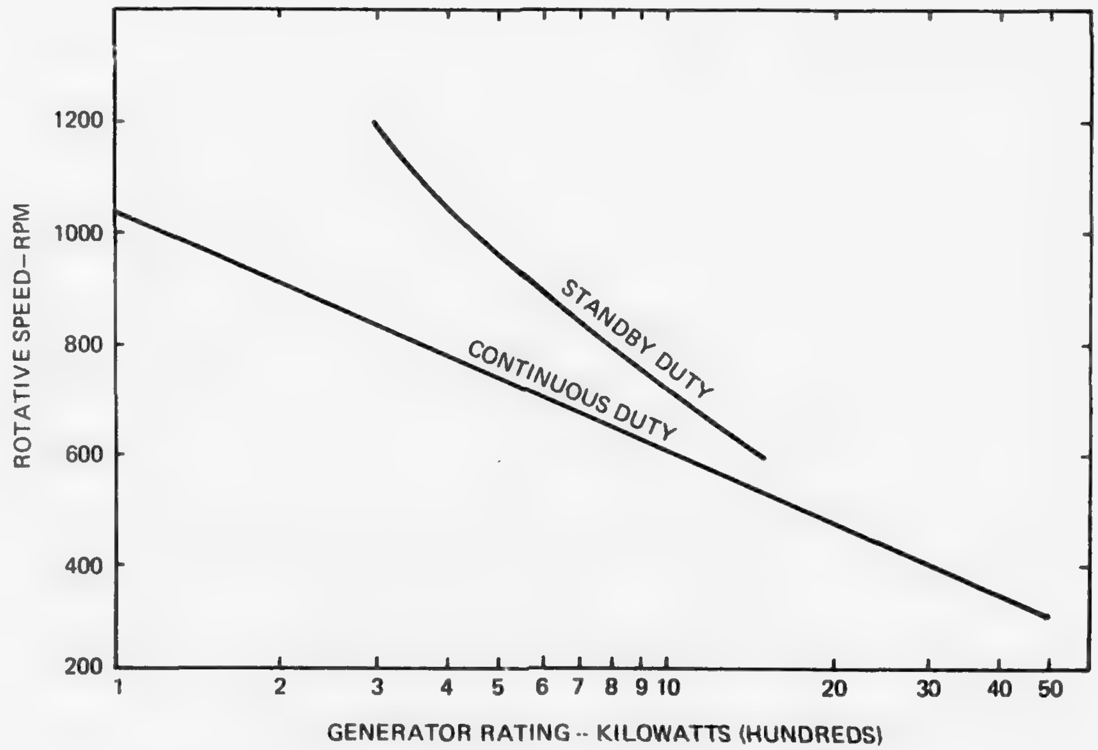


Figure 3. Diesel generator speed ranges for continuous duty and standby duty.

determine physical obstructions to the location of the plant and its distribution system. Considerations include topographical features, interferences with other buried distribution systems, groundwater problems, trenching impacts, the presence of adequate space for the plant, and possibly other factors.

5 LOAD ANALYSIS

After the candidate site or sites for the propsective heat recovery system have been identified, as shown in the first part of Step 3 of Figure 1, it becomes necessary to analyze the site's energy loads to establish their time profiles. The distribution of the energy loads is a major part of the information needed to define an optimum equipment configuration (see Chapter 6) and to conduct a detailed analysis of these configuration's performance (see Chapter 7).

The load analysis for a heat recovery system is very similar to load analyses performed as part of conventional HVAC design; however, it addresses the time dependence of the loads in greater detail, especially the time relationship between the mechanical loads (most commonly electrical generation) and the thermal loads.

This chapter discusses the following aspects of load analysis for heat recovery systems:

1. Required outputs

2. Selection of load analysis method

3. Required input data.

Required Outputs

The load analysis outputs required to define equipment configurations are the magnitude and time characteristics of the mechanical and thermal loads, specifically:

1. Direct mechanical energy requirements, by hour, by day of the week, by time of the year, and by schedule of utilization if utilization varies

2. Electrical loads, as a function of these same time factors

3. Thermal loads, categorized by temperature and temperature differential, as a function of these same time factors.

It may be acceptable to document facility loads less exhaustively if it has been decided previously that the heat recovery plant will operate on a selective energy basis in such a way that engine loading will always be reduced to a level determined by the thermal load. In this case, only the thermal load needs to be computed. Operating a selective energy plant in this fashion is unusual for HVAC loads but may be common in some industrial loads.

EXAMPLE. It is desired to locate a selective energy plant in an existing high-pressure steam plant for providing waste heat to boiler feedwater heaters. The electrical power from the selective energy plant will feed into the existing electrical network to reduce the amount of purchased power. The load on the network is such that the network can always absorb all of the electricity produced by the selective energy operators. In this case, the load analysis is reduced to a computation of the heat load profile of the feedwater heaters.

Selection of Load Analysis Method

Methods commonly used in conventional load analysis have different degrees of applicability for computing loads in heat recovery system analysis. Three conventional methods are discussed in this chapter:

1. Metering
2. Manual calculations
3. Computer programs.

Metering

Metering of loads can eliminate the need for load calculations in cases where the user facility already exists. Meters must be the recording type in order to give time profiles, and they must be installed for a period that includes a typical cycle of load conditions. The minimum duration of metering for space conditioning applications is generally 1 year, and this may be inadequate if atypical load conditions exist; for example, metering of heating loads will be misleading if the year includes an unusual winter.

Manual Calculations

Manual computation of electrical loads is based on analysis of the occupancy and usage of a facility to determine the individual components of electrical load at various times. Although a computer may be used to sum the individual loads, its use is not essential.

Thermal load peak values are commonly computed manually, especially for simpler facilities. Procedures for performing manual load calculations are contained in the 1975 ASHRAE *Handbook of Fundamentals*, in manuals published by major equipment manufacturers, and in other engineering references. Standard calculation forms are also available, most commonly from major HVAC equipment manufacturers. In most HVAC

applications, calculations of loads other than peak loads are not reliable when computed manually because there are thermal storage effects too complex to be included in normal manual calculations. Storage effects will cause major changes not only in the magnitude of computed loads, but also in the relative time phasing of the thermal load and electrical loads. Thus, in heat recovery analysis, manual calculations of thermal loads should be limited (1) to applications where heat storage effects are not significant, as in feedwater preheating, or (2) to applications where the magnitude of the thermal load can be adjusted to be compatible with the amount of thermal energy available, as in domestic water heating.

Computer Programs

Several standard computer programs provide load data for building structures having commonplace HVAC loads. Some are intended to be run directly by the engineer performing the analysis; others can be run by the proprietor of the program from information provided by the engineer. All of these programs require a substantial amount of user familiarity:

Computer programs enable the engineer to perform much more sophisticated calculations than are possible with manual methods. By maintaining stored data, they also reduce the need for data collection by the engineer; most programs have weather data tapes, and some have tapes of equipment characteristics. The principal load calculation programs are:

ECUBE. The ECUBE program was developed by the American Gas Association specifically for total energy applications. It includes a load calculation segment and segments which perform technical and economic comparisons of heat recovery plant configurations. The load calculation segment is less sophisticated than in some of the other programs. ECUBE is available at the Control Data Cybernet Centers that operate the CDC 6600 computer systems throughout the United States. Documentation is available from the American Gas Association, 1515 Wilson Blvd., Arlington, VA 22209.

APEC. The APEC program was developed by a nonprofit association of engineer/architect organizations and other interested agencies to apply computer analysis to the environmental systems for buildings. APEC may be used to prepare an input to ECUBE and is especially useful on larger projects involving several buildings or many zones. The input sheets are rather complex and consist of 11 different forms. A maximum of 39 different zones or buildings and up to 1000 rooms can be loaded into the program in one run.

TRACE. The Trane Air Conditioning Economics (TRACE) program, developed by the Trane Company, is a fairly sophisticated load program

which can incorporate the effects of many types of HVAC systems. TRACE has an equipment tape for HVAC components and is presently being modified to perform total energy equipment analyses.

NBSLD. The Center for Building Technology of the National Bureau of Standards developed the NBSLD program to compute the thermal loads of structures incorporating more advanced and innovative features than are provided for in other programs. The software for NBSLD can be obtained from the Bureau of Standards, but the user features provided with current commercial programs are not yet available.

ACCESS. The Alternate Choice Comparisons for Energy System Selection (ACCESS) program is an energy analysis program developed by the Electric Energy Association. It is available through utilities which are EEA members and through the Navy FACSO net.

NECAP. The NASA Energy Cost Analysis Program contains a load calculation segment, a system simulation segment, and an economic analysis segment. The system simulation segment allows modeling of a wide variety of HVAC systems. It has a very limited capability to model heat recovery from an engine generator.

Required Input Data

The detailed data requirements necessary for making either a manual or computer load analysis will be determined by the specific method selected. In the case of commercially available computer load programs, input data requirements can be discerned from the input sheets. The following data elements are typical of those required in HVAC applications:

1. Orientation, geographical location, and elevation of building

2. Areas, types, and colors of walls, ceilings, floors, partitions, windows, skylights, etc.

3. "U" factors for heat transmission

4. Temperature and relative humidity conditions to be maintained in each zone while occupied and unoccupied

5. Occupancy patterns

6. Operating practices such as shutoff temperatures and thermostat setback

7. Number of active and inactive occupants

8. Ratings of installed electric lights, motors, other heat-generating equipment

9. Ventilation system description and estimated infiltration gains

10. Description of space conditioning systems

11. Space conditioning system parameters, such as percentage of makeup air, reheat temperatures, etc.

Necessary data are most commonly acquired from the following sources:

1. Architectural, mechanical, and electrical plans

2. System specifications

3. Designer's HVAC calculations

4. Operating logs

5. Utilities bills and records

6. Discussions with personnel responsible for the operation and maintenance of the facility

7. Standard reference values for structures and components of similar type.

The purpose of this discussion has been to highlight aspects of load analysis practice which are of particular importance in dealing with heat recovery applications. Except for emphasis on the time relationship between electrical and heat loads, the engineer performing the load analysis for a heat recovery application will find the procedures used to be generally conventional.

6 CONFIGURING HEAT RECOVERY SYSTEM ALTERNATIVES

Introduction

After the suitability of a site for using recovery utilities is established and an analysis of the energy loads is made, candidate system configurations for a heat recovery plant that will fulfill these energy requirements must be defined. This chapter describes the design factors peculiar to heat recovery plants (Step 4 of Figure 1). Generally, applying these design guidelines will produce several candidate system configurations; a final selection is made from among these candidates using the detailed energy and economic analysis methods described in Chapters 7 and 8, respectively.

The development of candidate configurations should incorporate the following sequence of steps:

Assimilation of Equipment General Characteristics

The design of a heat recovery system for efficiency and reliability is dominated by the characteristics of the individual equipment components. Output, efficiency, and reliability may vary drastically by component or under different operating conditions for a given component. Hence, the designer should become thoroughly familiar with the range of characteristics of all equipment he may use, including:

1. The conditions of the energy provided, consumed, or transmitted by the equipment, i.e., quantities of heat, temperatures, and pressures

2. The efficiency of the equipment as a function of its energy input or output

3. Operational shortcomings or cautions associated with different modes of equipment operation

4. The relative cost of an equipment component compared to the cost of other components, or combinations of components, which perform the same function.

While most of the equipment used in a heat recovery system is identical to equipment used in conventional utilities plants, the range of these operational factors may be markedly different when the equipment is used in heat recovery applications. Therefore, it is essential to the validity of the analysis that equipment performance characteristics be known for the conditions under which the equipment will actually operate in the prospective system.

For the engineer familiar with conventional on-site utilities plants, the area of greatest novelty in dealing with heat recovery plant equipment is prime mover thermal characteristics. Unlike shaft output, which tends to be similar for all engines in a given category, thermal output varies markedly, both in quantity and in distribution of heat among heat recovery modes. Since engine thermal output is the basis of heat recovery system operation, the factors affecting the thermal characteristics of engines must be understood in detail by the engineer who develops a system configuration. These characteristics are presented in Appendix B, where they are illustrated by thermal performance curves for typical engines subject to varied operating conditions.

Assimilation of Heat Recovery Design Factors

It is not possible to provide a completely explicit sequence of steps to achieve an optimum heat recovery system configuration. The principal guide is a knowledge of the many heat recovery design factors which have been documented from past experience and theoretical analysis. Appendix C is a compilation of guidelines based on these factors.

Defining the Energy User System

In Chapter 4, the user system definition was oriented toward determining the magnitude of system loads; system definition is now oriented toward insuring compatibility of the user system equipment with the heat recovery system equipment. This aspect of the system configuration effort involves only conventional HVAC practice or other factors not unique to heat recovery.

Defining the Heat Recovery System

Developing an optimum configuration for the energy source components of a heat recovery system includes certain design steps or options which should be considered systematically in almost all applications:

1. Sizing of the overall heat recovery plant and selection of total energy or selective energy configuration

2. Selection of prime mover types

3. Selection of prime mover sizes

4. Selection of heat recovery equipment

5. Use of heat storage

6. Use of heat pumps

7. Use of prime mover clutch drives.

The remainder of this chapter will discuss these design options in detail. Decisions in these areas should be made in light of the general design factors cited previously in the Assimilation of Heat Recovery Design Factors section.

Plant Sizing and Selection of Total Energy or Selective Energy Configuration

The first issue to be resolved when establishing the prime mover generating capacity of a heat recovery plant is whether the installation is to be a total energy or a selective energy configuration. The following factors affect this choice:

1. A selective energy system must be connected to an outside electric power pool, but a total energy system does not.

2. If a selective energy configuration is used, the characteristics of the user system electrical load may greatly affect the system's accessibility to an outside electrical network and the rate structure of electricity purchased from the network.

3. If a selective energy system can be installed, it generally requires less capital investment than a total energy system; the selective energy system will probably not require reserve capacity, because the electrical network can be used to handle peak loads. Conventional boilers can be used to handle peak thermal loads.

4. If outside utilities fail, a selective energy system will not be able to provide peak user loads, and loads may have to be shed. Since a total energy configuration is always independent of outside utilities, it will have adequate capacity to handle the entire facility load.

The usual guideline for determining the capacity of a total energy plant is that the plant should reliably accommodate the maximum normal electrical load. Thermal loads in excess of those which can be met by heat recovery from prime movers are met efficiently with auxiliary boilers.

A similar guideline for sizing selective energy plants cannot be defined as clearly. If the shaft efficiency (essentially, the electrical generating efficiency) of the selective energy prime mover is greater than the overall efficiency with which purchased power is delivered, energy is conserved by the selective energy system in all

operating modes. However, selective energy prime movers usually do not have a large advantage in terms of shaft efficiency alone. With reciprocating engines, electricity is produced at roughly the same fuel efficiency at which electricity is delivered by large central utilities. Hence, the capacity of a typical reciprocating engine plant may be chosen from a broad range without severely affecting the plant's fuel efficiency relative to purchased power. With gas turbines, the efficiency of electrical generation may be substantially less than for central utilities. If this is the case, a primary objective in selecting the plant's generating capacity must be to overcome any energy lost as a result of lower shaft efficiencies through energy savings from heat recovery.

As an aid to achieving the maximum energy savings, curves similar to those in Figure 4 may be used as a graphical aid, using fuel consumption data for the prime movers applicable at a given installation. The desired objective in using these curves is to select a heat recovery system that maximizes the vertical distance between the energy consumption curve for purchased power. The former curve is computed using the equipment characteristics discussed earlier; the purchased power curve is computed using data discussed in Chapter 3. While this graphical technique is a convenient aid to initial system selection, it does not account for changes of equipment efficiency with load. The final analysis of the relative units of different heat recovery systems must be accomplished using the detailed procedures of Chapter 7.

The capital cost of a selective energy system can be decreased by reducing the size of the plant so that it provides only part of the thermal load, or so that it meets only the minimum thermal load. At the minimum load size, the cost effectiveness of the plant itself is maximized, because the plant may then operate at full load constantly, recovering all available heat. However, as the size of a selective energy plant decreases, the total amount of energy conserved also decreases.

If the shaft efficiency of the prime movers in a heat recovery plant is less than the efficiency with which purchased electricity can be delivered, the relative efficiency of a heat recovery plant deteriorates as the production of waste heat exceeds the thermal load. Figure 4 shows this effect. In fact, if adequate thermal load is not present when prime movers with low shaft efficiency are used, a heat recovery plant can become substantially less efficient than conventional utilities. This leads to the generalization that low shaft efficiency prime movers, i.e., gas turbines, should be used only when the thermal load remains high in relation to the amount of recoverable waste heat.

The example given in Figure 4 indicates that energy conservation is greatest with respect to purchased power when the thermal/electrical output ratio of the prime movers equals the thermal/electrical ratio of

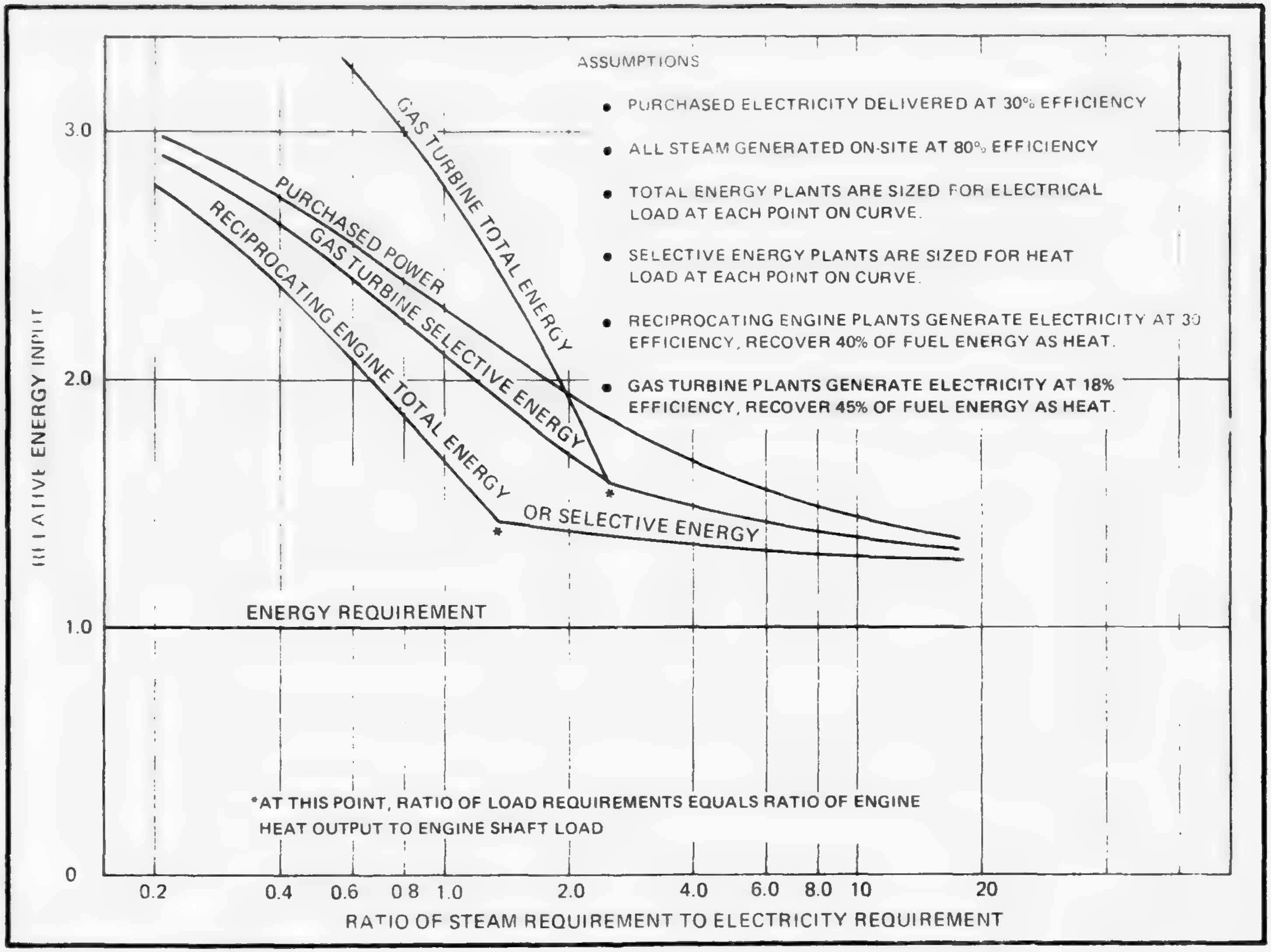


Figure 4. Fuel energy required to satisfy unit energy requirement with various utility sources.

the load. At lower ratios, waste heat is being discarded. At higher ratios, heat is increasingly being provided by boilers, which are common to both heat recovery plants and conventional plants.

If a total energy configuration is used, plant sizing must account for reserve capacity requirements and equipment reliability. The following factors should be considered when estimating reserve capacity:

1. Reserve capacity is required if growth of the facility load is expected. Information discussed in Chapter 4 should be reviewed to determine the extent of future growth.

2. Reserve capacity is required to allow for disablement of equipment, either for maintenance or as a result of mechanical failure. A guideline commonly used is that a plant should be able to serve its peak load with its largest generator disabled. By this rule, plant capacity becomes equal to the peak load plus the capacity of the largest engine. However, this is only a general guideline; it may be relaxed or made more stringent depending on the criticality of the load.

3. Engines used in heat recovery systems must be derated for continuous duty and for the type of heat recovery used. In the case of ebullient cooling, it is generally not desirable to exceed the derated full load rating even for short periods of time. With low temperature jacket cooling, it may be permissible to handle peak loads by loading engines above their continuous load ratings, thereby reducing engine size requirements. Such operation should be approached cautiously. The design of generators, heat recovery equipment, and auxiliaries must also be compatible with this expedient.

4. Some manufacturers of gas turbines offer replacement of failed units within a day or two. Exploitation of such rapid replacement should be considered a means of reducing reserve prime mover capacity when gas turbines are used. A contract or guarantee should be developed with the manufacturer if this arrangement is to be relied upon.

5. Load shedding should be considered as a means of reducing prime mover capacity requirements in total energy systems. The system should be designed so that load shedding is not employed routinely, but only under conditions of unusual equipment outage or extraordinary load. Reducing reserve capacity by load shedding can be accomplished only if a significant fraction of the load is noncritical, and if the noncritical load is separable from the critical load.

Selection of Prime Mover Types

Heat recovery has been accomplished with all of the major conventional prime movers used in stationary plants, i.e., with reciprocating

engines, gas turbines, and steam turbines. The conditions under which heat recovery is feasible, and the characteristics of the recovered thermal energy, differ substantially from one type of prime mover to another. Likewise, the type or types of prime movers to be selected depends on the technical characteristics of the environment and on budgetary constraints.

Appendix B presents the characteristics of reciprocating engines and gas turbines which enter into consideration when selecting prime mover types.

The design and application of heat recovery systems based on steam turbines are quite different from the design of heat recovery systems based on reciprocating engines and gas turbines. Also, within the category of steam turbine systems, there are significant differences between condensing and noncondensing systems. In general, any steam condensation taking place in a turbine prime mover wastes energy because latent heat of condensation is discarded. Hence, the most efficient steam turbine heat recovery systems employ backpressure turbines, in which all steam is exhausted into a user line, so that all latent and sensible heat, in principle, can be recovered.

The major drawback of backpressure systems with respect to other prime movers is that the ratio of mechanical output to thermal energy is very low. The ratio can be improved by using turbines with high inlet pressures; however, this expedient requires the use of high-pressure boilers, which are practical only at larger installations.

A backpressure steam turbine heat recovery system should be considered to supply large facilities if the thermal load is exceptionally high compared to the mechanical/electrical load or if a selective energy configuration is possible. If the thermal load is relatively large and a steam turbine configuration is not favorable, a gas turbine system may be more acceptable. Both steam turbines and gas turbines should be considered when the thermal load requires high-pressure steam. In almost all cases, reciprocating engines should be considered among the system alternatives, except when the thermal load requires mostly high-pressure steam.

Combining different types of prime movers in a heat recovery plant is a favorable approach in certain circumstances. The following considerations relate to combining prime mover types:

1. In general, a combination of reciprocating engines and gas turbines cannot achieve better energy conservation than reciprocating engines alone.

2. Capital cost may be minimized by using gas turbines to add peaking or reserve capacity to base-loaded reciprocating engines. If

the peaks are of short duration, or if there is a high thermal load during electric load peaks, the overall reduction of fuel efficiency may be small.

3. Using waste heat recovered from reciprocating engines and gas turbines will increase the cycle efficiency of condensing steam turbines by preheating feedwater.

4. Exhaust from gas turbines, which contains approximately 18 percent oxygen, may be used as preheated combustion air in boilers.

5. Combinations of prime mover types may be favorable where natural gas is available at favorable rates, but on an interruptible basis.

> EXAMPLE. In applications where thermal loads are high during periods of gas availability, dual-fuel gas turbines may be used efficiently in combination with oil-fueled reciprocating engines. In such a configuration, the gas turbine is used during periods of gas availability as long as its waste heat can be used. At other times, the gas turbine is used as a standby unit.

In all cases, combining prime mover types will increase the need for logistic support and personnel training.

Selection of Prime Mover Sizes

The choice of engine size involves establishing an optimum compromise between two sets of opposing factors:

1. Larger engines tend to be more efficient and cost less per unit of shaft output capacity than smaller engines

2. The use of a larger number of smaller engines improves reliability and allows the individual engines to run closer to full capacity; this provides greater efficiency and higher exhaust temperatures.

The following generalizations can be made to help quantify these factors:

1. In the size range of several hundred or more kilowatts, size becomes a minor factor in the efficiency of reciprocating engines. The efficiency of gas turbines appears to rise significantly with size in this range, although the number of gas turbine models available is so limited that the effect of size is difficult to discern.

2. Diesel engine shaft efficiency varies little in the range of 60 to 100 percent load, usually peaking at some intermediate value. Below about 50 percent load, efficiency begins to drop off more rapidly. The shaft efficiency of gas turbines drops severely and continuously as load is decreased below full load. (See Appendix B for a detailed discussion of reciprocating engine and gas turbine efficiency characteristics.)

From the standpoint of efficiency, distribution of engine sizes should be based on the load profile. If the load is always a large fraction of the peak load, a high engine loading can be maintained with few engines. If there are long periods during which the facility load becomes a small fraction of peak load, using a small number of large engines will frequently cause individual engine loading to be inefficiently low. Figure 5 is an example of how individual engine load varies with total load as a function of the number of engines employed. In this example, all engines are the same size, and the engine controls are set to keep a minimum number of engines on line, with the load distributed equally among all running engines.

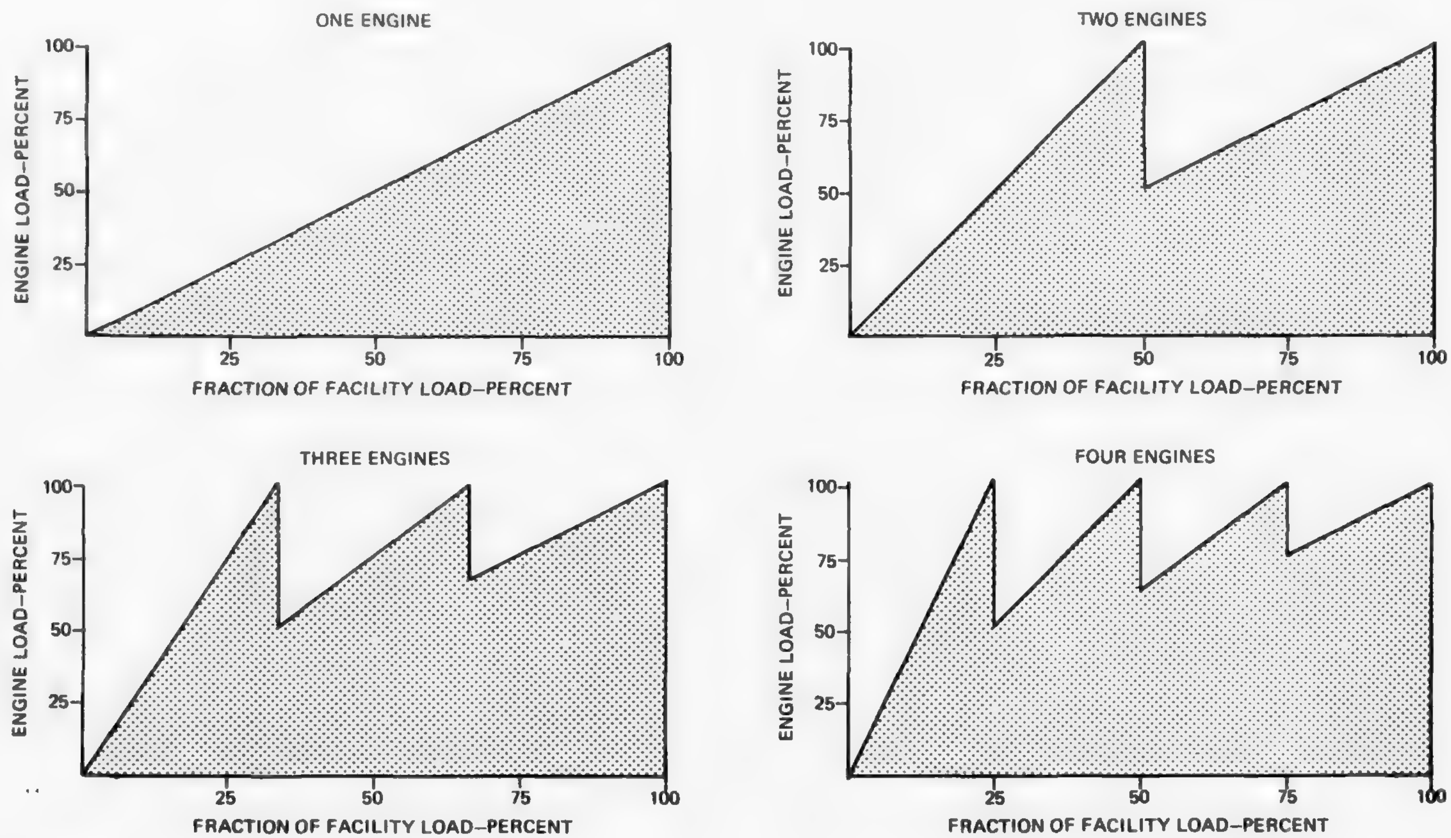
> EXAMPLE. A night load at a facility is 10 percent of the peak load. In a two-engine configuration, the engine which runs at night will have a load of only 20 percent. In a four-engine configuration, the engine which runs at night will have a load of 40 percent. With typical engines, both fuel efficiency and exhaust heat recovery are significantly better at 40 percent load than at 20 percent load.

A method of maintaining high engine load during an extended period of low facility load is to include one engine which is smaller than the others.

> EXAMPLE. In a configuration of two engines, one of which is twice the size of the other, average engine loading is essentially the same throughout the range of demand as it would be in a configuration where three engines of identical size are used. (This is true provided that the smaller engine of the first configuration is run during periods of low demand, is dropped when the rising facility load requires the larger engine, and remains off until both engines are needed.)

Using engines of dissimilar size creates an increased logistic burden which is not justified unless the facility exhibits low loads during a significant fraction of time. When engines of dissimilar size are desirable, the added logistics requirements can be minimized by using engines which have a high degree of parts commonality.

The specific engine sizes should be based on a careful examination of the load profile to insure that engines need not be stopped and started frequently throughout the daily load cycle.



ASSUMPTIONS:

- NO RESERVE CAPACITY
- LOAD DISTRIBUTED EQUALLY AMONG ALL RUNNING ENGINES
- A MINIMUM NUMBER OF ENGINES ARE OPERATED

Figure 5. Average engine load as a function of number of units.

SUMMARY EXAMPLE. At a particular facility, the typical daytime load fluctuates from approximately 700 to 800 kW; the typical night load is 200 kW, and it is desired to have a total generator capacity of 1500 kW. The desired generator capacity could be met with two 750-kW generators. However, maintaining optimum engine loading with this configuration would require frequent starting and stopping of one of the engines. A better configuration would be three 500-kW generators, so that two engines on line would be operating near peak efficiency (assuming reciprocating engines) with adequate margin in excess of the range of fluctuation. However, the night load on a single engine is still undesirably low. A further improved configuration would consist of one 300-kW generator and two 600-kW generators. With the latter configuration, the night facility load provides 66 percent loading to the smaller engine, and the day facility load provides 78 to 89 percent loading to a combination of the smaller engine and one larger engine. With the smaller engine down for maintenance, the facility day load still provides 58 to 67 percent loading to the two larger engines.

Selecting Heat Recovery Equipment

The heat recovery equipment configuration should be selected on the basis of the features of the various heat recovery methods which may be employed and on the need to provide compatibility between the thermal characteristics of the heat sources and the heat users. This section discusses these two decision factors.

Characteristics of Heat Recovery Methods

The following are methods of heat recovery which are practical with contemporary prime movers.

Steam Turbine Heat Recovery. Recovery of heat from a steam turbine is accomplished by exhausting steam from the turbine directly into the user system. Steam turbine heat recovery systems using backpressure or extraction turbines involve no novel design features unfamiliar to conventional steam plant design. Feedwater treatment in backpressure systems used to provide heating steam is more extensive than in conventional condensing steam systems, because condensate returned from heating systems is generally contaminated.

Exhaust Heat Recovery. Exhaust gas carries away between 25 and 35 percent of fuel input energy in conventional four-cycle reciprocating engines--both compression and spark-ignited. In two-cycle engines, exhaust may carry away up to 40 percent of fuel energy, due to the

scavenging air flow. The fraction of this energy that can be recovered depends on the design of the exhaust gas heat exchanger, and ultimately, on the temperature differential which can be maintained across the heat exchanger. For producing low-pressure steam, recovery of 40 to 50 percent of exhaust heat is typical at full load, with this fraction decreasing as higher steam pressures are produced. Unfortunately, exhaust temperature falls drastically as engine load decreases, a particularly severe condition in diesel engines, which have a low exhaust temperature profile overall. In two-cycle diesel engines, the flow of scavenging air reduces exhaust temperature to the point that exhaust heat recovery at low engine loads may become impractical, despite the fact that the total quantity of exhaust in two-cycle engines is exceptionally high.

The low temperature limit for exhaust heat recovery is established by the need to keep the gas side of the heat exchanger at 212°F (100°C) or higher to prevent condensation. When the heat recovery medium is steam, the heat exchanger will be kept at an adequate temperature by the steam, so that a heat exchanger of any size may be used. If the heated medium is water at a temperature below 212°F (100°C), heat exchanger size must be limited to maintain adequate gas side temperature at all engine loads. This tends to reduce the heat exchanger efficiency.

In gas turbines, 70 to 90 percent of fuel energy, or virtually all of the recoverable waste heat, is carried away in the exhaust stream. The fraction of fuel energy going to exhaust heat rises as turbine load is reduced, but the temperature of the exhaust falls. Heat exchanger considerations are generally the same as with reciprocating engine except that the need to maintain low backpressure is especially critical with gas turbines.

<u>Jacket Heat Recovery in the Liquid State</u>. Jacket coolant carries away approximately 20 to 30 percent of fuel energy in four-cycle engines, both compression and spark-ignited. Larger engines tend to discard relatively less jacket heat. In two-cycle engines, much less heat is available than in four-cycle engines. Virtually 100 percent of rejected jacket heat is recoverable. The temperature at which jacket heat can be recovered is determined by the temperature of the jacket coolant, minus the drop across the heat exchanger, if one is used. Reciprocating engines operate conventionally with jacket outlet temperatures in the range of 190° to 210°F (87° to 98°C). Systems using 220°F (103°C) pressurized hot water from reciprocating engines have been used and function reliably. The relative output of jacket heat may be reduced significantly if the jacket temperature is raised, since the reduced temperature gradient forces cylinder heat into the jacket coolant.

<u>Ebullient Heat Recovery</u>. Ebullient cooling is a means of recovering heat from an engine jacket by allowing the cooling water to partially

flask into steam within the engine. Virtually all heat is rejected as latent heat of the steam, and the temperature drop across the engine is negligible. Ebullient cooling has two main advantages: (1) it provides low pressure steam, which is needed to drive absorption chillers at full capacity, and (2) it allows both exhaust and jacket heat recovery to take place in a common boiler (Figure 6). In addition, heat exchanger selection problems are minimized, because the gas side is maintained at a temperature that provides a nearly optimum compromise between heat transfer efficiency and prevention of condensation.

A major disadvantage of ebullient cooling is that the heat transfer capacity of the steam formed within the engine is much less than that of water. Hence, there is a tendency for hot spots to occur in the region of steam formation, i.e., around the upper cylinders and valves, where cooling is most critical. Experience indicates that some engines tolerate ebullient cooling well, while others do not. In any case, ebullient cooling is a critical mode of engine operation, because many engine components are stressed to nearly the limits of their performance. Also, the possibility of catastrophic damage to the engine will be aggravated if the system fails, for example, if there is a loss of coolant pressure.

Steam separators used with ebulliently cooled engines are similar to conventional low-pressure boilers and require auxiliary equipment normally associated with such boilers, such as high and low water alarms, feed pumps and controls, and blowdown fittings. Other equipment is required to prevent excessive steam formation inside the engine and to dispose of excess steam.

Lube Oil Heat Recovery. Approximately 5 percent of fuel energy is rejected from a typical four-cycle engine to the lube oil as waste heat. Lube oil heat rejection is higher in two-cycle engines. In two-cycle opposed piston engines, where separate cylinder head cooling is absent, lube oil may carry away up to 20 percent of fuel energy. The temperature of lube oil heat recovery is limited by the maximum permissible temperature of the oil, which is approximately 130°F (54°C) and by the temperature drop across the heat exchanger.

Aftercooler Heat Recovery. The aftercooler of a turbocharged engine is frequently connected in a common circuit with the lube oil cooler. The heat recovered from these units is more than 5 percent of fuel energy at full load and may exceed 15 percent at low loads. Thus, the combination of aftercooler and oil cooler is a low-temperature heat source which provides an amount of heat that fluctuates relatively little with engine load.

Radiation Heat Recovery. Thermal radiation from conventional four-cycle engines carries away approximately 5 percent of fuel energy

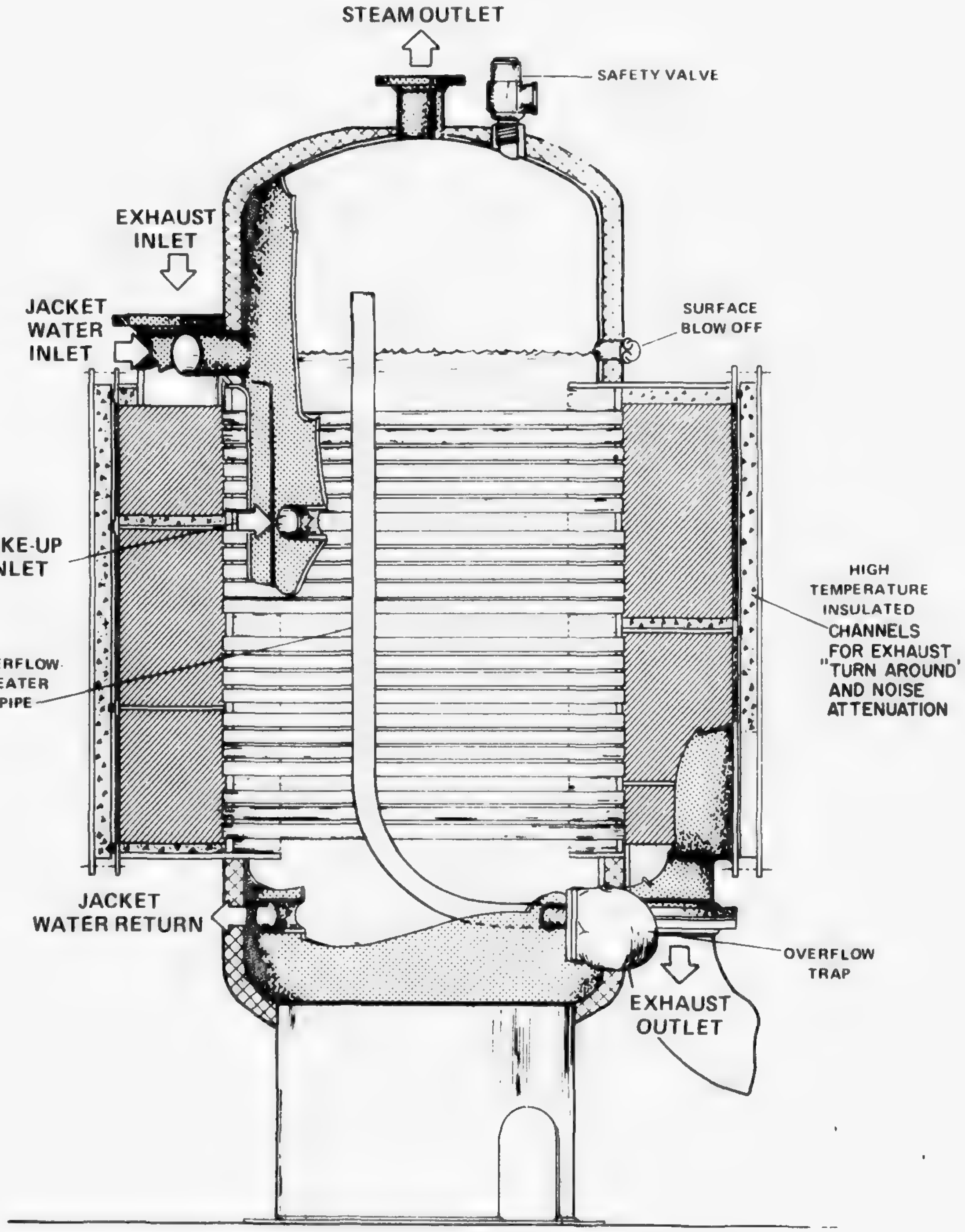


Figure 6. Waste heat boiler combining ebullient cooling and exhaust gas heat recovery. (Adapted from illustration by Killebrew Engineering Corporation.)

at high engine loads, and somewhat more at low loads. Radiation from gas turbines and two-cycle engines is much lower. While radiation is generally considered to be nonrecoverable, using a runaround loop or an air source heat pump in the heated engine space may be a good means of recovering radiation loss for space heating.

The configuration of a heat recovery system will exploit one or more of these methods. With steam turbines, only exhaust steam heat recovery is significant, and with gas turbines, only exhaust heat recovery is significant. In the case of reciprocating engines, the recovery of jacket heat, exhaust heat, and possibly oil/aftercooler heat are all significant and may be combined in many ways.

It is not difficult to select an acceptable heat recovery method for space heating. Almost all space heating equipment operates efficiently at temperatures and with temperature differentials which can be provided by exhaust heat and by jacket coolant at conventional engine temperatures. Lube oil coolers and turbocharger aftercoolers provide temperatures suitable for low-temperature heating systems and domestic water heating.

In systems where cooling is required, the need to provide relatively high temperature heat to absorption chillers dominates the choice of heat recovery method. To allow the recovery of jacket heat for this application, ebullient jacket cooling has been widely used, despite the criticality of this mode of heat recovery. More recently, accumulated negative experience with ebullient cooling and the improved availability of low temperature performance data for absorption chillers have motivated the design of cooling systems using lower temperature pressurized hot water to drive absorption chillers. Using lower input temperatures reduces the capacity of the chillers so that a greater capital investment for chillers is needed to fulfill a given cooling requirement. However, the criticality of operating such a system is substantially reduced, and the range of selection of engines with demonstrated suitability for heat recovery applications becomes much broader.

Thermal Compatibility Between Heat Source and Heat Users

The overall configuration of the heat recovery system must achieve a match among the following factors:

1. Heat requirements and heat available from prime movers

2. User system temperature requirements and temperatures available from prime movers

3. Necessary temperature differentials of user systems and prime movers

4. Heat utilization from different modes of heat recovery.

Maintaining balance between the heat requirement of the user and the heat available from the system prime movers generally involves no configuration problems. If adequate heat is not available from the prime movers, conventional boilers are used to provide supplemental heat. If too much heat is produced, it is rejected to the environment. Most commonly, a cooling tower is used to condense excess steam or to cool excess heated water. An alternative to this method, which reduces the capital and operating cost involved in the operation of a cooling tower, is to regulate exhaust heat recovery by diverting exhaust gas around the exhaust heat exchanger. This method is less conventional and may involve using equipment which is difficult to obtain or is not adequately proven.

Reconciling the temperature requirements of the user system with the temperatures available from prime movers is accomplished by selecting and adjusting the temperature characteristics of either or both of these. The range of flexibility which is available for accomplishing this in space conditioning systems was discussed earlier.

Matching the temperature differentials within an overall system may require extensive analysis. Heating equipment components can frequently be operated over a wide range of temperature differentials, but their efficiency, cost, and energy requirements vary substantially as the temperature drops across the units change. When hot water is used as an energy input to absorption chillers, the capacity of the chiller drops rapidly as the hot water discharge temperature decreases, i.e., as the temperature differential increases for a given inlet temperature. The temperature differential needed across the engine (for jacket heat recovery) and/or heat exchanger (for exhaust heat recovery) will dictate the minimum drop across the chiller, and hence the chiller's capacity. Matching temperature differentials also provides the most complex control problems, particularly where several modes of heat recovery are used.

Balancing the flow of heat between different modes of heat recovery and heat usage is dependent on the system's temperatures and temperature differentials. Generally, transfer of heat from a high temperature system to a lower temperature system involves little difficulty. If a heat exchanger (for sensible heat transfer) or steam convertor (for latent heat transfer) is used, flow in the primary circuit can be adjusted to provide the temperature differential needed by the heat user. If a system involves the transfer of heat between modes of heat recovery, the design configuration should insure that an excess of heat will occur in the higher temperature system.

EXAMPLE. Jacket heat recovery is used with a reciprocating engine to provide heat to the building's core zone, while exhaust heat from the same engine is used to supply a higher temperature perimeter system. The core and perimeter systems are interconnected so that excess heat from exhaust gas can be fed into the lower temperature core zone. To achieve maximum efficiency from this configuration, the zoning of the building and the relative loads of the core and perimeter zones must be designed so that any imbalance between core and perimeter heating will always appear as an excess of perimeter zone heat. If the reverse occurs, the lower temperature heat of the core zone cannot be fed into the perimeter system.

Use of Heat Storage

Heat storage can improve the performance of heat recovery systems in two principal ways:

1. In total energy systems, energy efficiency can be improved by storing waste heat produced during periods of high mechanical or electrical load and releasing it when engine heat output is low. Heat storage is useful only if there are periods when the thermal demand of the user system significantly exceeds the heat output of the engines, so that stored heat can be used. Heat storage cannot compensate a chronically inadequate thermal load.

2. In selective energy systems, recovery of equipment capital cost can be improved by using heat storage to provide a more uniform heat recovery profile to the engines, so that fewer engines are needed and higher engine utilization is maintained. Heat storage also allows the efficient use of engines for peak shaving without the need for a simultaneous thermal load.

Presently, water is the most economical and trouble-free medium for storing heat or cold. Unfortunately, since only sensible heat can be stored in water at useful temperatures, the required quantity of water is large.

In most cases, only a fraction of engine heat output must be stored, so that required water volumes are reduced accordingly. The actual storage volume required in a particular installation is determined by the largest uninterrupted deficit of heat recovery in the daily operating cycle, and by the amount of excess heat produced during the rest of the day to service this deficit.

EXAMPLE. Figure 7 depicts the profiles of engine heat production and total system heat requirement for a

particular system. During two periods, labeled E_1 and E_2, respectively, the production of waste heat by the engines exceeds the instantaneous system requirements, and during two other periods, labeled D_1 and D_2, there is a deficit of waste heat. The period D_1 is clearly the period of largest deficit, and should be the target of the storage volume calculation. Assume that at the end of D_1, at 0500, the amount of stored heat is zero. During period E_1, heat is accumulated; during D_2, some of this heat is consumed. During E_2, the remaining stored heat is augmented by still more excess heat. The design goal is that at the beginning of D_1, at 2200, the amount of heat remaining in storage should equal the total deficit of D_1. If this deficit cannot be met by storage of all the excess heat produced during the day, extra heat should be produced with boilers. If more heat is available in storage at 2200 than is needed during D_1, the heat storage system is unnecessarily large.

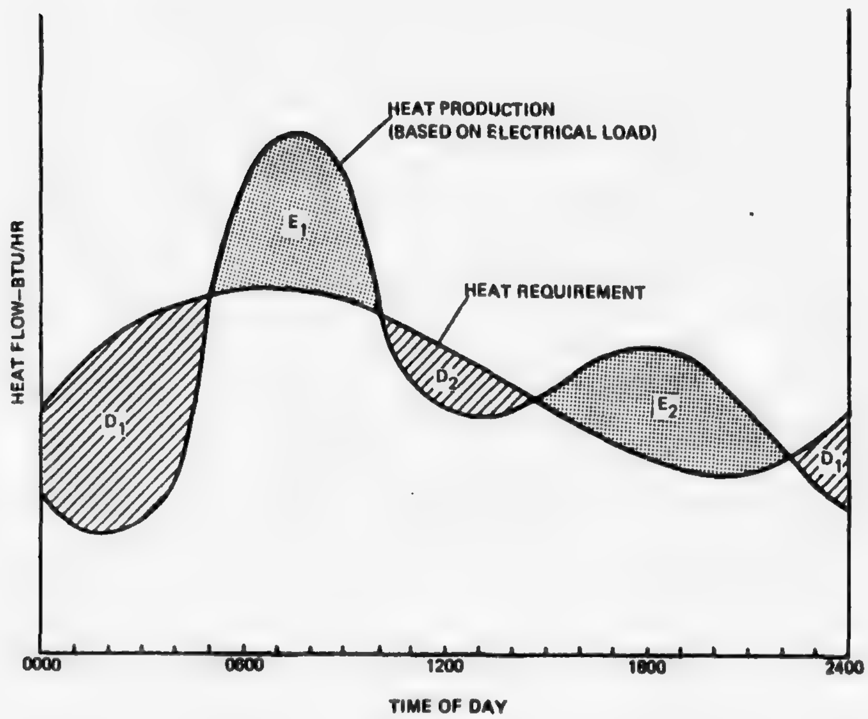


Figure 7. Example of heat storage requirement.

Quantitative analysis of actual heat storage capacities can be computed, if load profiles are available, by graphical analysis such as that used in Figure 7, or by one of the more sophisticated computer load programs.

The type of heat storage facility to be used depends on the insulation requirements of the storage vessel, permissible cost, and whether total daily waste heat production exceeds the total daily heat recovery deficit.

Large, insulated above-ground tanks lose only a few percent of stored heat daily, but are expensive and occupy substantial space. Less expensive methods for storing heat, such as using commercial septic tanks as containers, may be acceptable in specific configurations. Generally, relative insulation requirements diminish as water volumes increase because the relative heat transfer surface is reduced as volume increases.

When heating systems are used whose system temperatures vary with changing weather conditions, a heat storage system is a convenient buffer between the heating system's variable temperature conditions and the prime mover's fixed temperature conditions.

Use of Heat Pumps

Heat pumps are particularly favorable for use with heat recovery systems. Standard references, such as the ASHRAE *Guide and Data Book* series, should be reviewed for a general discussion of heat pumps. The following aspects should be considered concerning their use with heat recovery systems:

1. A heat pump driven by a prime mover which employs heat recovery is the most energy-efficient available means of providing low-temperature heat. Figure 2 in Chapter 4 illustrates the range of energy efficiencies for such a system compared to the efficiencies of boilers and heat pumps driven by purchased power.

2. The cooling efficiency of a heat recovery system using a heat pump (or any compression chiller) driven by a prime mover is much higher than that of a heat recovery system using only absorption chilling.

3. Using a prime-mover-driven heat pump expands the range of conditions under which good load balance can be maintained. If the overall shaft load becomes too small for adequate balance, heat pump load can be added to maintain thermal output. If the overall shaft load becomes too great to maintain adequate balance, heat pump load can be dropped in favor of engine heat and absorption cooling.

4. The heat available from heat pumps is at a lower temperature (typically a maximum of 120° to 130°F (48° to 54°C) for acceptable efficiency) than the heat available from engine exhaust or cooling jackets. Hence, heat from the heat pump and from the engine must be used in separate systems, or higher temperatures from the engine will have to be sacrificed.

5. The low heating temperature available from heat pumps eliminates the possibility of their use with certain major categories of heating systems. If a heat recovery system will be provided for a facility that has a heating system, the compatibility of heat pumps with the existing system must be established.

6. A heat pump can efficiently provide simultaneous heating and cooling by heating with the condensor circuit and cooling with the evaporator circuit. If both circuits are used for space conditioning, the efficiency of the heat pump becomes especially high, because the temperature differential across the heat pump is low.

7. In applications where heat pump systems heat and cool simultaneously, the daily heating and cooling load profiles are typically out of phase. However, heat storage can easily be made part of such a system to achieve maximum efficiency.

Use of Prime Mover Clutch Drives

Electrically driven motors and attendant electrical losses can be eliminated if major mechanical loads are driven directly by prime movers. If a load fluctuates or is not continuous, as in the case of chillers and heat pumps, a favorable configuration may be one in which the prime mover is both permanently connected to a generator and connected to the fluctuating mechanical load by a clutch. In this way, engine loading can be maintained at a desired level. The disadvantage of this arrangement is that disablement of the prime mover will make the driven equipment nonfunctional.

7 ENERGY EFFICIENCY ANALYSIS OF CANDIDATE SYSTEMS

The previous chapter provided design guidelines for selecting heat recovery system configurations appropriate to the user facility environment on the basis of essentially qualitative design factors. Selecting the best of these candidate configurations is accomplished by detailed quantitative analysis of the energy efficiency and economics of each system. Energy efficiency analysis is discussed in this chapter and economic analysis is discussed in Chapter 8. These two chapters compose Step 5 of Figure 1.

Detailed energy efficiency analysis focuses on two factors:

1. The relationship of the system's thermal load to the heat output of the prime movers must be computed over a yearly operating cycle. Whenever the instantaneous waste heat production of the prime movers exceeds the instantaneous system requirement (including any heat storage capacity), energy is lost. These losses must be integrated over the course of a yearly cycle and compared to the gross energy requirement to give the net system efficiency.

2. The efficiency of the system components varies with changes in operating conditions. The aggregate efficiency of the system components during a yearly cycle must be computed by integrating the instantaneous efficiencies of the system components over the year.

In the case of selective energy systems, which always operate at a level determined by the thermal load, only the second of these factors is applicable, and it may be possible to make a reasonably accurate estimate of the performance of such a system with manual computation techniques. For most total energy systems, and for selective energy systems operated to reject recoverable heat, accuracy requires computer methods. In no case is it permissible to rely solely on peak load values.

Four topics are covered in this chapter:

1. Use of computer programs

2. Equipment performance data

3. Level of specification

4. Refinement of candidate configurations.

Use of Computer Programs

As discussed in Chapter 5, several computer programs are available

for computing the thermal load of a structure throughout a yearly operating cycle. However, only one of these, the ECUBE program, presently has the capability of providing a yearly total of the instantaneous heat balances between the heat recovery system and the user system. The ECUBE program uses the electrical/mechanical load and engine heat recovery characteristics, as a function of the electrical load, to determine the amount of heat recoverable for every hour of the year. For each hourly calculation, the available heat is related to the heat load for that hour. If insufficient heat is available from the engines, additional heat is provided by other equipment (if any) specified by the engineer. Equipment interconnections, startup and shutdown limits, and in the case of engines, load distribution among units are all specified parameters in the ECUBE program. ECUBE is actually composed of three subprograms, each of which has its own input and is billed separately:

1. The ENERGY subprogram can be used independently as a conventional load analysis program. The output of this subprogram includes monthly totals of heating, cooling, electrical, and process loads; monthly peak loads; and hourly load breakdowns of the peak heating day. The hourly computations are not displayed but are stored in the computer for use by the other two subprograms.

2. The EQUIP subprogram uses inputted equipment performance data and the hourly load data computed in the ENERGY subprogram to compute utilization of recoverable heat, rejection of recoverable heat, fuel consumption by type of fuel, and running time of individual units of major equipment. Each is presented in monthly totals. Equipment running profiles give a breakdown of total hours at 10 percent increments of load over 1 year.

3. The ECON subprogram uses inputted economic parameters, such as initial investment and interest rates, and operating data computed in the EQUIP program to compute life cycle costs by year.

TRACE, a sophisticated load calculation program developed by the Trane Company, is currently being modified to incorporate heat recovery as a source of thermal energy. Other programs may be similarly modified in the future.

Knowledgeable use of a computer program such as ECUBE, which is learned by study of program reference manuals and interaction with the program's parent organization, completes the detailed energy efficiency analysis of a candidate heat recovery system configuration. The following sections provide guidance in providing input to the program and in using the results.

Equipment Performance Data

Efficiency analysis requires the inputting of equipment performance data into the computer program or other analysis technique. Instances of inadequate performance and complete failure to improve energy efficiency in past heat recovery installations have been traceable to the use of improper equipment performance data in both the analysis and system design. Performance data that reflect the actual conditions under which the equipment will operate in the system must be used.

Particularly in the case of engines, adequate thermodynamic information is not currently available as part of the standard technical specifications ordered by most manufacturers. The desired categories of data listed in Appendix B are generally available in the research organizations of those manufacturers whose engines have been used in heat recovery service, but substantial time may be required by the manufacturers to make these data available. Nonetheless, the engineer should insure that the appropriate performance data are on hand before attempting to conduct the detailed system feasibility analysis.

Difficulty may also be encountered in acquiring part load performance curves for other major equipment, but this situation is improving as designs increasingly focus on energy efficiency. In the case of absorption chillers, caution should be exercised to insure that performance data reflect the method of throttling control which is used in the system configuration.

Level of Specification

Detailed designs of all candidate configurations are not needed for feasibility analysis and would, in fact, represent an unjustified expenditure of resources. However, the configuration should be specified in sufficient detail so that detailed energy efficiency and cost analyses can be conducted for each configuration. Specifically, each configuration should include the following levels of detail:

1. All equipment that significantly affects the energy efficiency of the overall system must be specified in detail sufficient for its energy characteristics to be documented throughout its operating range. In the case of engines, it may be necessary to specify a particular engine model. In the case of major energy-handling equipment with more standardized characteristics, such as centrifugal chillers, it is sufficient to specify the performance curve of the generic type of equipment. In the case of units having only a small contribution to the energy efficiency of the system, such as small motors and pumps, it is sufficient to specify a single average figure for energy efficiency.

2. Connections and interdependencies of system components must be specified to a sufficient level of detail to avoid assumptions that may lead to an incorrect analysis of system performance.

3. Specified startup and shutdown sequences, loads at which additional units are picked up, and the method of distributing loads among components may have marked effects on system efficiency. The ECUBE program particularly provides for specifying these factors.

> EXAMPLE. In the feasibility analysis for a total energy system, the most favorable system was one employing two reciprocating engines and a gas turbine, where the gas turbine was used to carry peak loads. The original engine loading sequence specified that all engines should build up to full loads as the facility load increases, and should remain at full load as successive engines are started. However, the initial computer analysis indicated that the nature of the facility load caused the gas turbine to always operate at loads less than 10 percent, which is extremely unfavorable for gas turbine efficiency. A change in the engine loading sequence to divide the facility load evenly among all running engines resulted in an overall improvement in energy efficiency of several percent.

It is appropriate to emphasize that the specification of equipment which is accomplished for the feasibility analysis must be carried forward into the design of the actual installation. In soliciting bids for major equipment, it is vital that the bid specifications call for equipment thermally similar to that which is used in the candidate configurations.

> EXAMPLE. In an actual case, exhaust heat recovery equipment was installed on engines used to provide power to a communications station. Because of a change in plans, a number of housing units and other facilities originally intended to be powered by the units were not used as engine loads. In addition, security requirements for the communications equipment required that at least two engines always be running. The engines purchased for the facility were very large units, so that the two engines which were running were almost always at low loads. It is doubtful that exhaust recovery would have been efficient with any engines under these conditions, but to aggravate the problem, the bid specification allowed two-cycle engines to be purchased. Because of the extremely low exhaust temperature which is characteristic of two-cycle engines at low load, the exhaust heat recovery system was a failure. (It is interesting to note that in

the application for which waste heat was needed, jacket heat recovery would have been completely satisfactory, but it was not employed.) While it does not appear that a proper feasibility analysis was ever conducted for this system, this example does dramatize the effect of using equipment whose specifications are not adequately constrained.

Refinement of Candidate Configurations

The first detailed analysis of each candidate configuration will provide a gross ranking for comparison with other candidates and will suggest changes to improve its performance. Unless the most favorable configuration appears to operate as efficiently as the environment permits, iterations of the analysis should be performed, including such changes as are indicated by the first analysis. If the first analysis indicates that one or more systems are close in performance to the most favorable, all of those with potential for improvement should be included in the iterative analyses.

Changes to configurations should be directed at eliminating indications of inefficiency or uneconomical operation which appear in the analysis. Such indications include:

1. Operation of a unit of major equipment for only a few total hours, except for necessary standby units

2. Operation of a prime mover at low loads for a large fraction of its total operating hours

3. Failure to use a fraction of the waste heat produced by an engine

4. Inability to provide electrical and thermal load requirements at all times, or, in the event that load shedding is used routinely, the need to shed load excessively.

The sensitivity of configuration performance to changes in the facility load should also be examined. As one extreme, system performance should be computed on the basis of wartime conditions or other conditions of maximum facility utilization. The extreme of low utilization should be judged from experience and future utilization projections. If the performance of a particular candidate heat recovery system demonstrates undue sensitivity to changes in facility utilization, the configuration should be modified to eliminate the sensitivity, or a configuration with less sensitivity should be chosen.

EXAMPLE. An initial feasibility analysis indicates that a configuration consisting of two diesel engines and a gas

turbine is the most cost-effective candidate. However, a 20 percent increase in average load, expected under wartime utilization, places so much of the load on the gas turbine that fuel efficiency is substantially reduced. A configuration consisting of three diesel engines proves to be only slightly less attractive in the initial analysis and suffers no degradation of efficiency at the higher load. Therefore, the latter system should be selected.

8 ECONOMIC ANALYSIS OF CANDIDATE SYSTEMS

The decision to select a particular candidate system for construction will generally be based on its economic performance as well as on its energy efficiency. In evaluating economic performance, a trend has developed toward selection on the basis of total life cycle costs rather than on the basis of first cost alone. Various directives now make life cycle cost analysis mandatory in DOD. Life cycle cost analysis may be performed manually or by computer. Extensive guidance within the Department of Defense prescribes the methods and assumptions to be used.

The most common computer methods available for performing energy analyses also include routines for performing life cycle cost analyses. These routines are satisfactory for fulfilling military cost analysis requirements. The computer program used for the energy analysis should also be used for the economic analysis, with input parameters such as interest rates and service life being taken from the same sources.

This chapter represents the last part of Step 5 of Figure 1 and discusses the input information needed to perform economic analyses and the use of the results obtained. Seven topics are discussed:

1. Existing economic analysis directives

2. Defining life cycle costs

3. Defining capital costs

4. Defining operating and maintenance costs

5. Comparing heat recovery system cost with conventional system cost

6. Performing iterations to designs to establish minimum cost systems

7. Analyzing sensitivity to nonconfiguration factors.

Existing Economic Analysis Directives

The following definitive instructions for performance of economic analyses of construction projects presently exist:

1. DOD Instruction 7041.3 defines the elements of life cycle costs.

2. AR 37-13 sets forth specific instructions and procedures to be followed by the Army in performing economic analyses costing more than $200,000.

3. AR 415.2 requires consideration of life cycle costs as part of studies of proposed military construction.

4. DAEN-MCE-U's "Engineering Instructions for Preparation of Feasibility Studies for Total Energy, Selective Energy and Heat Pump Systems" dated 1 July 1975 provides guidance for life cycle costing.

5. NAVFAC Instruction 11010.53A prescribes guidelines for the preparation and submission of economic analyses as justification for proposed Military Construction (MILCON) Investments exceeding $300,000.

6. NAVFAC Publication P-442, the Economic Analysis Handbook, provides Navy instructions for economic analyses.

These instructions require that economic analyses be performed according to the present worth method of analysis. The applicable factors to be used in computing an economic measure of merit are described. Payback periods and interest rates to be used are specified. In addition to these instructions, other applicable references identified later in this chapter should be reviewed before initiating the economic analysis.

Defining Life Cycle Costs

Life cycle costs include all expenditures associated with the construction and operation of a system over a span of time defined as the life of the system. These expenditures are defined by Department of Defense Instruction 7041.3 to include recurring as well as non-recurring investment costs, and costs of operation and maintenance. The following guidelines should be followed in defining life cycle costs:

1. The life cycle costs should be listed by the year in which they are expected to be incurred

2. All estimates of future costs should be shown in constant dollars (not adjusted for inflation)

3. The sensitivity of a set of proposals to possible changes in future prices should be investigated by analyzing a reasonable range of prices.

Defining Capital Costs

The capital cost of a system includes the system first cost, subsequent investment costs, and working capital costs.

System First Cost

System first cost includes all items that are necessary prior to beneficial occupancy and start of normal operations. Equipment components of system first cost include:

1. Major system equipment such as engines, generators, heat exchangers, and heat recovery boilers

2. Installation of major equipment

3. Land and site improvements, including demolition of existing structures

4. Building and structures

5. Inside piping and electrical subsystems

6. Instrumentation

7. Auxiliary subsystems such as fire protection, fuel storage, cooling towers, and water treatment.

In addition to equipment purchase and installation costs, system first cost can include the following items:

1. Interest costs during construction

2. Contingency to allow for uncertainties

3. Legal fees, permits

4. Design and engineering fees

5. Supervision of plant erection.

Subsequent Investments

Although many fixed capital cost items, such as purchase of land and prime movers, will be nonrecurring, certain investment items may require replacement during the period of time covered by the feasibility study. Care should be taken to insure that such future capital costs are included in the analysis.

Working Capital

Items which compose working capital costs include:

1. Fuel inventories and money to meet startup payrolls
2. Readily available cash for emergencies
3. Any additional cash required to operate the system.

Sources of Data

Sources of cost estimating data include equipment manufacturers, NAVFAC and Corps of Engineers headquarters offices, previous studies and reports, other publications, and consultants. NAVFAC Publication DM-10, *Cost Data for Military Construction*, contains data useful for estimating military construction costs. A source of data on relative costs of different equipment is the *Report on Total Energy Feasibility Criteria* prepared for the U.S. Army Engineers Power Group in December 1973.

Costs obtained from references should be updated in the study year through use of a cost index. A few of the more frequently used indices are:

1. Construction and Building Indexes, *Engineering News-Record*
2. *M&S Equipment Cost Index*
3. *Nelson Refinery Construction Index*
4. "Plant Cost Index," *Chemical Engineering*.

Rather than depending solely on cost estimating nomographs and inflation indices, current prices of major equipment items should be determined by contacting equipment manufacturers or their representatives. It should be recognized that costs given by suppliers for estimating purposes are approximations to actual bid costs.

Defining Operating and Maintenance Costs

The operating and maintenance costs must be determined on the basis of an analysis of the requirements and plans for operations and maintenance. These cost elements will include:

1. Fuel and lubricants
2. Water
3. Electricity

4. Operating and/or patrolling labor

5. Operating supplies, chemicals, etc.

6. Janitorial services

7. Laboratory costs and technical services

8. Maintenance costs

   a. Employee labor

   b. Contract labor

   c. Materials.

In addition to these cost elements, overhead charges may be made against the system to cover costs of security, timekeeping, payroll processing, and so forth. Labor costs should include fringe benefits.

In a separately located heat recovery plant, all of the personnel working at the plant will be fully chargeable to the plant. If the system is collocated with other utility systems to which operators are presently assigned, it may be possible to allocate operating labor proportionately.

Specific operating and maintenance cost data for a large number of conventional reciprocating engine generator plants are contained in the *Report on Diesel and Gas Engines Power Costs* of the American Society of Mechanical Engineers.

Comparing Heat Recovery System Cost With Conventional System Cost

Both the investment and operating cost elements for a heat recovery system will differ from those of a conventional system. In the detailed economic analysis of candidate heat recovery systems, the cost of providing utilities in a conventional manner is used as the standard of comparison. The following qualitative differences in cost can be expected to exist between heat recovery systems and conventional utilities.

Investment Costs

The investment costs of the heat recovery system can be compared to those for a conventional system on the basis of costs for design, equipment, and facilities.

Design Costs. Because heat recovery systems are new to many designers, design costs will probably be higher and may include some learning and contingency costs.

Equipment Costs. The cost of some components of a heat recovery plant will be higher because they are specialized items not produced in large quantities. The absorption refrigeration units used with a heat recovery system will have a higher investment cost than centrifugal units. Engines and possibly absorption chillers may be derated in heat recovery service, thus increasing the cost per unit capacity. On the other hand, costs for some elements of conventional systems, such as boilers, will be eliminated. The heat recovery system's electrical generating capability may eliminate the need to install emergency generating equipment.

Facilities Costs. The increased amount of equipment needed for a heat recovery system requires a larger enclosure than a conventional system that consists of a boiler plant with purchased electricity. However, the proximity of the heat recovery system to the user facility may eliminate the need to construct new or replacement distribution lines from a central power plant.

Operating Costs

Operating costs that may be affected by a heat recovery system include fuel, operating and maintenance labor and equipment, and costs for purchased utilities.

Fuel Costs. A heat recovery system may require use of a lighter and more expensive oil than can be used at a central power plant, thereby causing an increase in the unit cost of input energy. However, this increase should be more than offset by the recovery of heat energy.

Operating and Maintenance Labor and Materials Costs. A remotely located heat recovery plant may require full-time, around-the-clock personnel for operations and maintenance. Compared to a conventional system, the more complex heat recovery system will require higher skills. The cost of maintenance materials would be expected to be essentially independent of the system's location.

Purchased Utilities Costs. If electrical power is presently purchased from an outside source, the electrical generating capacity added by a heat recovery system may reduce or eliminate demand charges. If gas is used as a fuel, gas demand charges may be either increased or decreased, depending on the manner in which gas purchases are altered.

Performing Iterations to Designs to Establish Minimum Cost Systems

The preceding chapters discussed design options primarily in the context of technical performance. The initial economic analysis of candidate configurations may suggest changes in the configurations that will improve cost performance. The following are possible qualitative changes to configurations that may be employed for the purpose of reducing system costs:

1. Adaptation of existing equipment: using existing equipment that has a technical capability for adaptation to a heat recovery system to reduce investment costs.

2. Plant sizing: sizing the heat recovery system to serve a load large enough to permit economies of scale that will minimize the contribution of operating and maintenance labor costs to total costs of energy produced.

3. Load optimizing: selecting a load that permits the heat recovery system to operate at a high level of efficiency and to make full use of recovered heat.

4. Plant location: locating the heat recovery system at or near an existing utilities plant to use existing O&M labor and to minimize additional labor costs. If possible, the heat recovery system should also be located where there is already fuel storage, where existing distribution lines may be used, and where absorption refrigeration systems are installed.

5. Fuel: selecting a fuel assuring long-term availability, and, if possible, having a cost advantage over existing fuels. For example, future prices of natural or synthetic gas may increase significantly and may ultimately exceed costs of petroleum products; moreover, future availability of gas is uncertain. Such conditions would eliminate the current economic advantages of gas.

Within each configuration, the quantitative effect on economic performance of altering the capacity of the system should be considered for all configurations that survive as candidates after the first iteration, provided that flexibility in altering capacity exists. This will usually be the case in selective energy systems and will be true in total energy systems where there is flexibility in the user loads to be served.

Both minimization of cost and achievement of a high level of absolute cost savings, within the limitations of available investment funds, should be sought. For example, in an analysis of selective energy configurations, the alternative with the highest payback ratio

may have a capacity less than the total load requirements. In such cases, the cost effectiveness of increases to plant capacity should be tested to attempt maximization of the absolute cost savings. The plant capacity of a candidate configuration should be increased up to the point where incremental investment no longer provides sufficient incremental cost savings.

Analyzing Sensitivity to Nonconfiguration Factors

The relative economic performance of different configurations may vary with factors not directly related to the configuration design. Where these factors cannot be specified with certainty, the sensitivity of the systems' relative economic performance should be examined over the range of uncertainty within which these factors may vary. In particular, repeated iterations of the economic analysis should be performed to determine the sensitivity of economic performance to:

1. Interest rate
2. Fuel and purchased electricity costs
3. Functional life
4. Investment and operating costs
5. Load profile.

The repeated iterations necessary to perform a sensitivity analysis generally require only a small fraction of the effort needed to complete the initial analysis. The results of the sensitivity analyses may be displayed graphically to show the conditions under which an alternative becomes more or less economically attractive. Economic measures of merit, such as payback ratio, rate of return, or payback period, may be plotted against variables such as load profile or fuel costs to display their impact on cost effectiveness of the TE system.

APPENDIX A: WORKSHEETS FOR HEAT RECOVERY SYSTEM FEASIBILITY ANALYSIS

INSTRUCTIONS FOR USE

The purpose of these worksheets is to provide a file of information from which a systematic and complete assessment of heat recovery system feasibility can be made. The worksheets follow closely the descriptive procedure for feasibility analysis presented in the publication *Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities*, of which these worksheets are an appendix. The numbering of the worksheets corresponds to the chapter numbers of the Procedures as follows:

Review of Potential Site Environment	- Worksheet Series A	- Chapter 3
Site Selection and Analysis	- Worksheet Series B	- Chapter 4
Load Analysis	- Worksheet Series C	- Chapter 5
Heat Recovery System Configuration	- Worksheet Series D	- Chapter 6
Efficiency Analysis	- Worksheet Series E	- Chapter 7
Economic Analysis	- Worksheet Series F	- Chapter 8

At appropriate points in the worksheets, DECISION points are included. At these points, it may be possible to reduce the results of previous worksheets to a single summary result, reducing the volume of information which must be handled in actually carrying out the analysis; or, it may be possible to terminate the analysis at an early point, eliminating the need to expend further effort. The action to be carried out at each DECISION point is indicated on the worksheet.

Often, not all of the information called for in the worksheet will be readily available. The words, "if available," indicate that a major expenditure of effort is probably not justified for the indicated item of data. The engineer performing the analysis must make the final decision as to the importance of including a particular item of data which proves difficult to acquire.

Prior to using the worksheets, the engineer performing the analysis should become thoroughly familiar with the content of the Procedures. In the course of developing the worksheets and carrying out the analysis, reference to Figure 1 of the Procedures will prove useful.

SERIES A - REVIEW OF POTENTIAL SITE ENVIRONMENT*

1. Thermal Requirement

Check:

___ Substantial thermal load in the locale of the construction project

___ Significant existing or potential prime mover shaft load within efficient heat transmission distance, and/or significant electrical load within overall facility

___ Significant time overlap between thermal load and shaft load, including overlap made possible by heat storage

DECISION. If fewer than all three of these are checked:

☐ Discontinue the analysis; heat recovery is not feasible. Otherwise,

☐ Continue.

* Cf. Chapter 3 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

2. Operator Personnel

Will personnel of adequate skill levels be available for operating a heat recovery plant, either at the site, patrolling, or on a contract basis?

___ Yes

___ No

DECISION. If No,

☐ Discontinue the analysis; heat recovery is not feasible. Otherwise,

☐ Continue.

3. <u>Environmental Impact</u>

Does it appear that a major environmental impact will occur as a result of the installation of a heat recovery system?

___ Yes

___ No

DECISION. If Yes,

☐ Perform environmental impact assessment before proceeding, and attach to this sheet. Otherwise,

☐ Continue.

4. Fuel

Diesel Fuel:

Price structure

Present:

Projections (if available):

Contracts available

Natural Gas:

Rate structure

Present:

Category	________	________	________
Commodity charge	________	________	________
Demand charge	________	________	________
Projections (if available):	________	________	________

Contracts available, including types and conditions of delivery

Coal (only if steam turbine systems may be considered):

Grades of coal available __________ __________ __________

Price structure __________ __________ __________

Contracts available

5. <u>Competing Electric Utilities</u>

Rate Structure

Present:

Consumption charge

Demand charge

Fuel and other surcharges

Projections (if available):

Reserve Capacity or Undercapacity

Fuel Efficiency to Point of Use (if available)

Types of Fuels Consumed (for coal, give grades of coal which can be burned)

Legislative Restrictions on On-Site Generation

___ None, or:

6. Existing On-Site Utilities
Services Available, Including Inactive Equipment (Give Status)

Capacities, Reserve Capacity, or Undercapacity

Aggregate Efficiency to Point of Use

Type of Fuel Used

DECISION. (Summary for Worksheets A/4, A/5, and A/6) A/4, A/5, and A/6 will in most cases not provide directly sufficient information on which to base a decision regarding heat recovery feasibility. They should be retained in the working file as sources of decisionmaking information in Worksheet Series B and D and as input data for Worksheet Series E and F.

SERIES B - SITE SELECTION AND ANALYSIS*

1. Review of Facility Plans

For each of the sources cited, obtain the following information on facilities which may be incorporated into the heat recovery system or whose utilization may affect the system.

a. Present Utilization of Related Structures:

Sources (Check and relate to information collected)

_____ Facility master plan

_____ Staffs of tenant commands

_____ Other (specify).

* Cf. Chapter 4 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

b. **Future Utilization of Related Structures:**

Sources (Check and cite)

_____ Facility master plan

_____ Staffs of tenant commands

_____ Headquarters offices responsible for facilities utilization (only if tenant commands cannot provide information)

_____ Other (specify).

c. **Plans for Construction, Demolition, and Abandonment of Related Structures:**

Sources (Check and cite)

_____ Facility master plan

_____ Facility engineer/PWC

_____ Current list of requested/approved construction projects

_____ District office/field division (only if information is not available locally)

_____ Other (specify).

d. **Plans for Modification, Improvement, Addition, or Phase-out of Onbase Utilities:**

Sources (Check and cite)

_____ Facility master plan

_____ Facility engineer/PWC

_____ Current list of requested/approved construction projects

_____ Utilities director

_____ District office/field division (only if information is not available locally)

_____ Other (specify).

Worksheet B/1
Page 5

e. **Anticipated Emergency/Standby Power Requirements for Related Structures:**

Sources (Check and cite)

_____ Staffs of tenant commands

_____ Headquarters offices responsible for type of structure (only if information unavailable from tenant command)

_____ Other (specify).

f. Impact on Other Planned Energy Conservation Projects (especially, whether loads or load profiles will be altered by other projects):

Sources (Check and cite)

_____ Current list of requested/approved construction projects

_____ Staffs of tenant commands

_____ Facility, district/field division, and headquarters offices responsible for energy conservation

_____ Other (specify).

DECISION: The following sites should be considered further as potential components of a heat recovery system:

2. <u>Existing Waste Heat Sources</u>

a. List all of the following which are within efficient heat transmission range of potential thermal energy users:

___ Existing long-running electrical engine generators

___ Existing emergency/standby engine generators

___ Existing prime movers driving mechanical loads. (Describe driven equipment.)

b. Characteristics of existing prime movers:

___ of ___ (Use separate sheet for each engine model.)

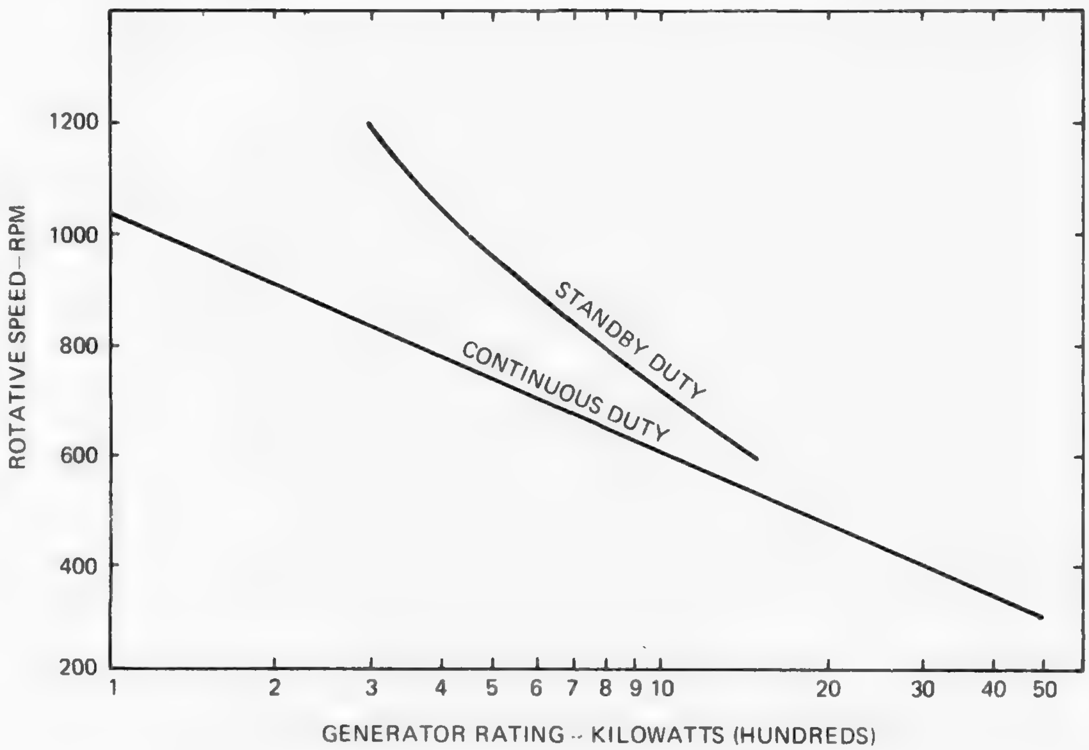
______________________ Manufacturer/model number

Utilization:

From site:

Number of engines of this model	________
Type (Otto, diesel, gas turbine)	________
Turbocharging/aftercooling	________
Current fuel	________
Size (number of cylinders, bore/stroke)	________
Speed	________
Rated continuous power	________
Installation date	________
Electrical output (kW, volts)	________

(Plot present operating point of engine.)



From manufacturer:

Is model still in production? __________

Quantity built __________

Usable fuels __________

Reliable heat recovery modes,
with engines in installed configuration

Reliable heat recovery modes, with engines modified

Modification requirements (each mode)

Modification costs (each mode)

Derating necessary for continuous service

Engine thermal data available? __________

On order? __________

Received? __________

3. Potential Waste Heat Users

a. Applications:

Check possible users of waste heat in vicinity of project:

___ Space heating

___ Space cooling

___ Domestic hot water

___ Cooking and steam tables

___ Laundry

___ Combined cycles

___ Desalination

___ Other (specify).

Worksheet B/3
Page 2

b. Individual Facilities:

___ of ___ (Use separate sheet for each structure under consideration.)

____________________ Structure identification

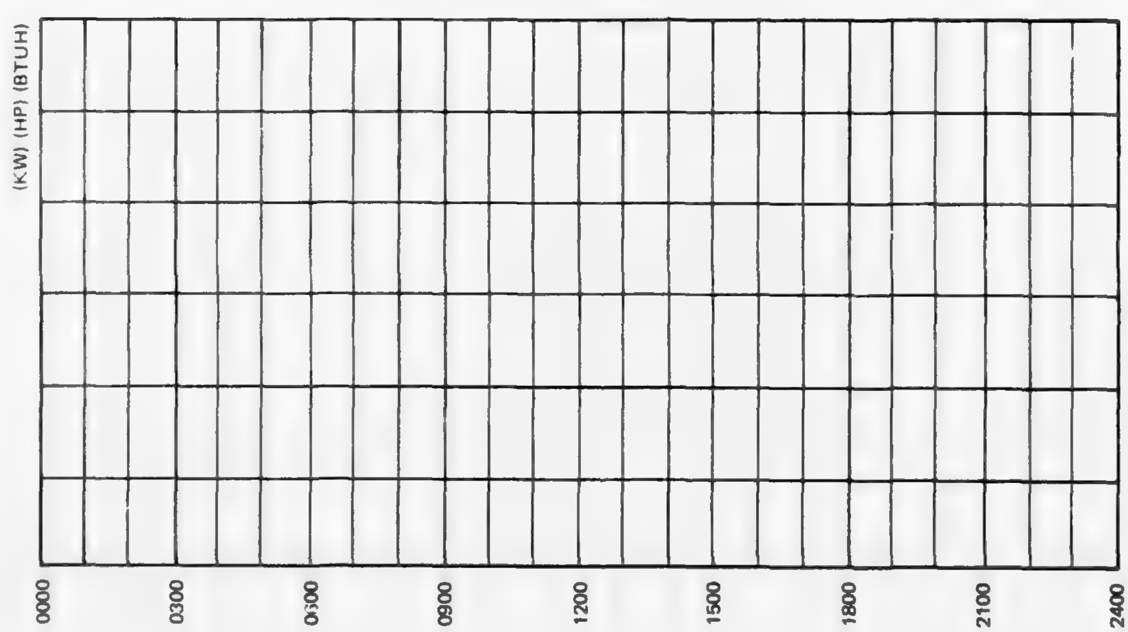
Load characteristics (Estimate, and indicate basis of estimate. Accuracy sufficient only for initial selection of candidate sites is required. Electrical loads should not include heating or cooling equipment.)

Peak electrical or mechanical load ______ kW (hp)

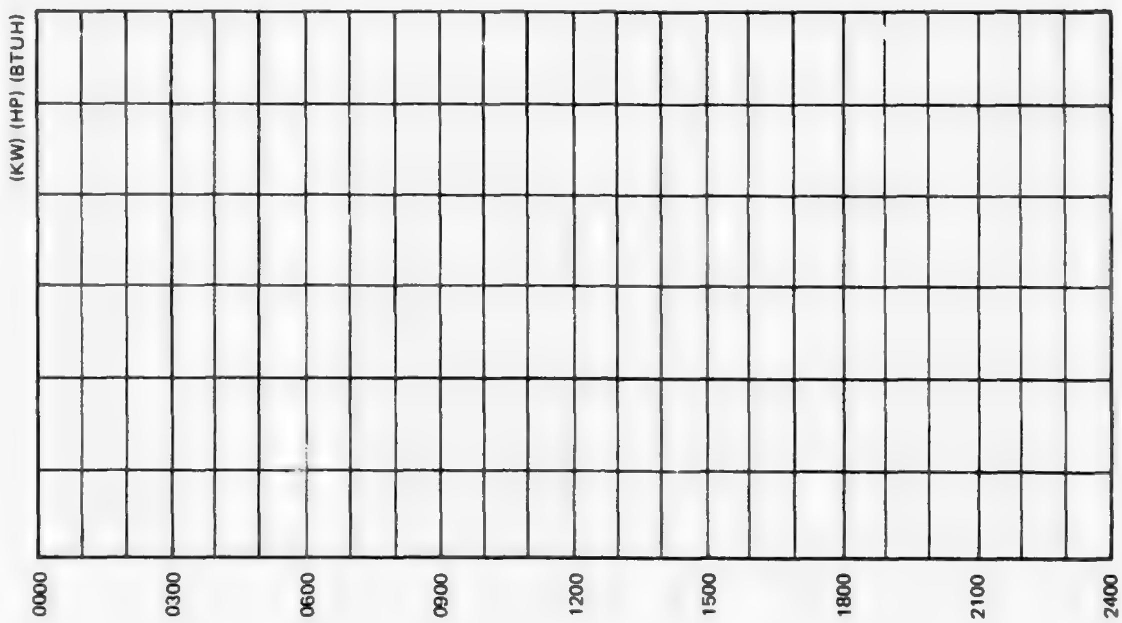
Peak thermal load ______ Btu/hr

Daily electrical/mechanical load profile and daily thermal load profile (graph together, for each day type):

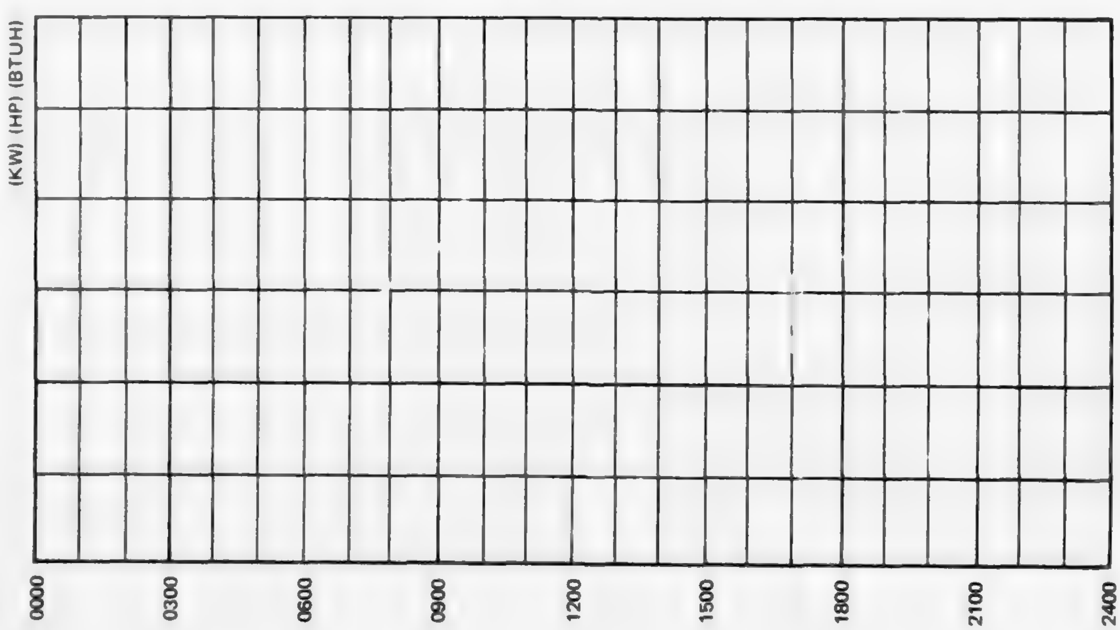
At peak summer thermal load -



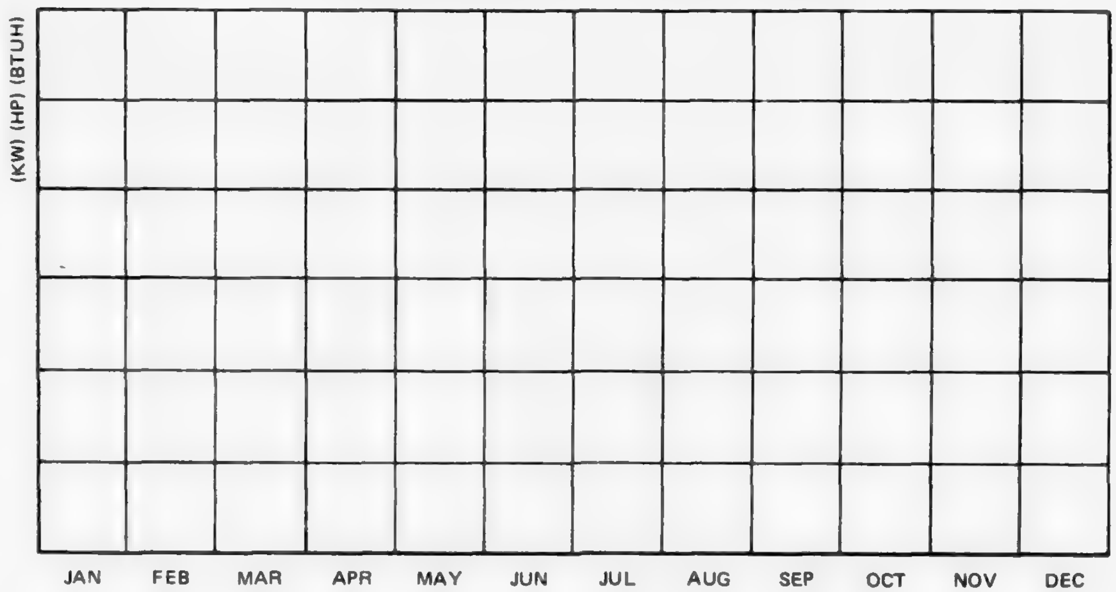
At peak winter thermal load -



At minimum yearly thermal load -



Seasonal electrical/mechanical load profile
and seasonal thermal load profile
(graph together, for each day type) —



Availability of flexible thermal loads (describe):

Worksheet B/3
Page 5

Existing thermal equipment belonging to structure:

Boilers:

Number	______	______	______
Pressure	______	______	______
Fuel(s)	______	______	______
Capacity	______	______	______
Age (approximate)	______	______	______

Heating system:

Distribution system type

Heater type(s)

Compression chillers:

Number	______	______	______
Capacity	______	______	______
Type of drive	______	______	______
Age (approximate)	______	______	______

Absorption chillers:

Number	______	______	______
Capacity	______	______	______
Methods of control (if known)	______	______	______
Age (approximate)	______	______	______

Small air conditioners:

Number ______ ______ ______

Type ______ ______ ______

Size ______ ______ ______

Age (approximate) ______ ______ ______

External utilities:

Electricity:

Proximity to distribution system

kVA capacity

Steam:

Availability/proximity

Supply pressure ____________

Condition of steam lines

Condition of condensate lines

Topographical features:

(Describe potential physical interferences obstructing the distribution system of potential heat recovery system)

c. Combinations of Loads:

____ of ____ (Use separate sheet for each combined configuration)

______________________ Identification of configuration

(If more than one facility was documented on Worksheets B/3.b as a potential site for heat recovery, consider combinations of sites, where possible, to achieve improved overall load characteristics. Indicate advantageous combinations and their composite characteristics.)

DECISION. (Summary for Worksheet Series B). List the combinations of structures, energy user systems, and existing energy sources to be given further consideration for use of heat recovery.

SERIES C - LOAD ANALYSIS*

(Perform detailed load calculations of the candidate sites selected in Worksheet Series B. If a computer program is used, follow the instructions provided in the input instruction manual. If Worksheet Series E requires the use of computerized analysis, a consolidated computer program which is suitable for both Series C and E should be employed. For manual calculations of HVAC loads, use ASHRAE methods.)

Attach output of load analyses of individual structures and combinations of structures selected in Series B.

* Cf. Chapter 5 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

Worksheet D/1
Page 1

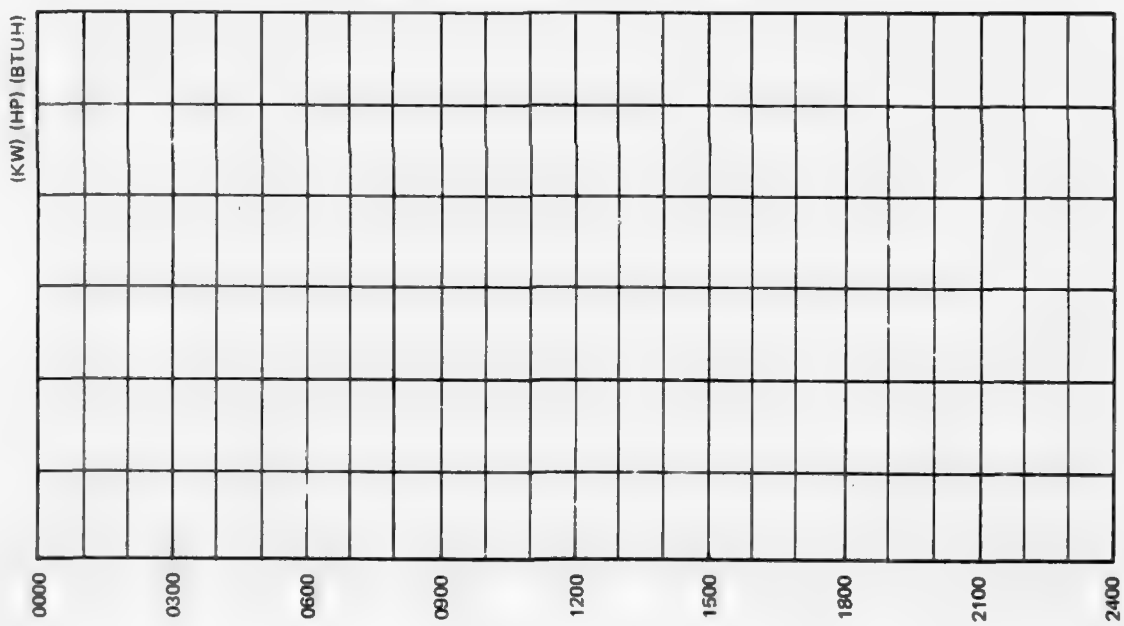
SERIES D - HEAT RECOVERY SYSTEM CONFIGURATION*

(The following steps relate to the development of the energy supply side of the heat recovery system. Definition of the conventional energy user elements has been accomplished in Worksheet Series C.)

1. Relationship to Network Consumption Profile

Graph daily electrical load profile for each candidate structure and group of structures (from Worksheets B/3. b or C), present daily purchased electricity profile of entire facility, and daily power consumption profile of external network (if available).

At peak summer thermal load -



* Cf. Chapter 6 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

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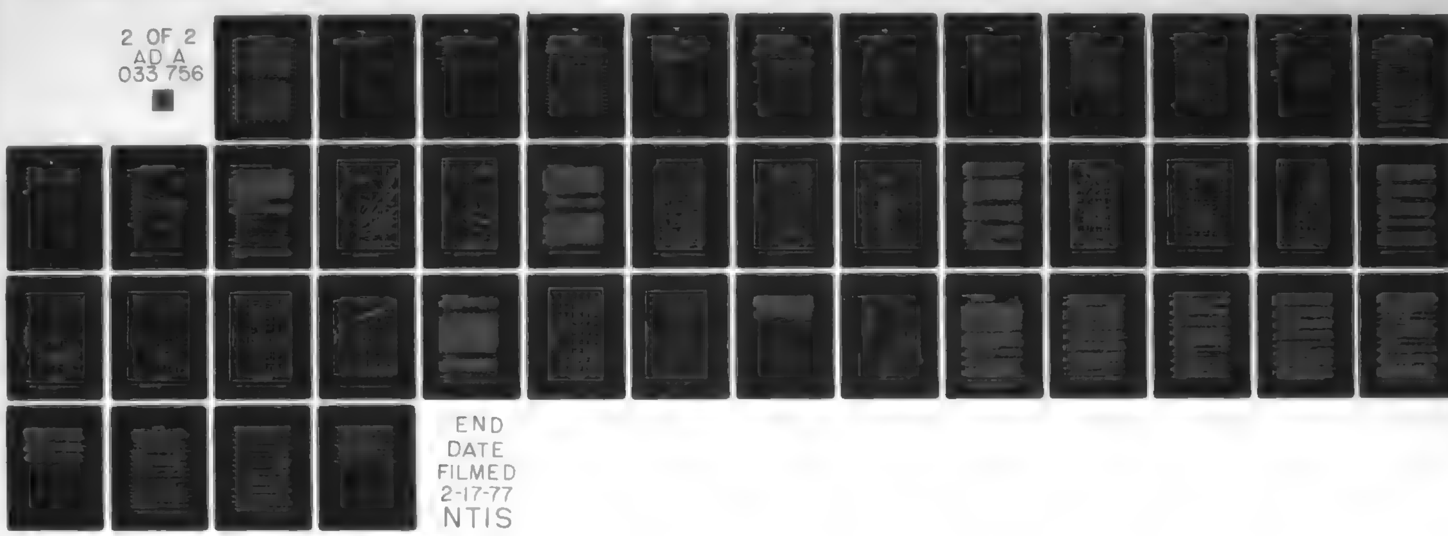

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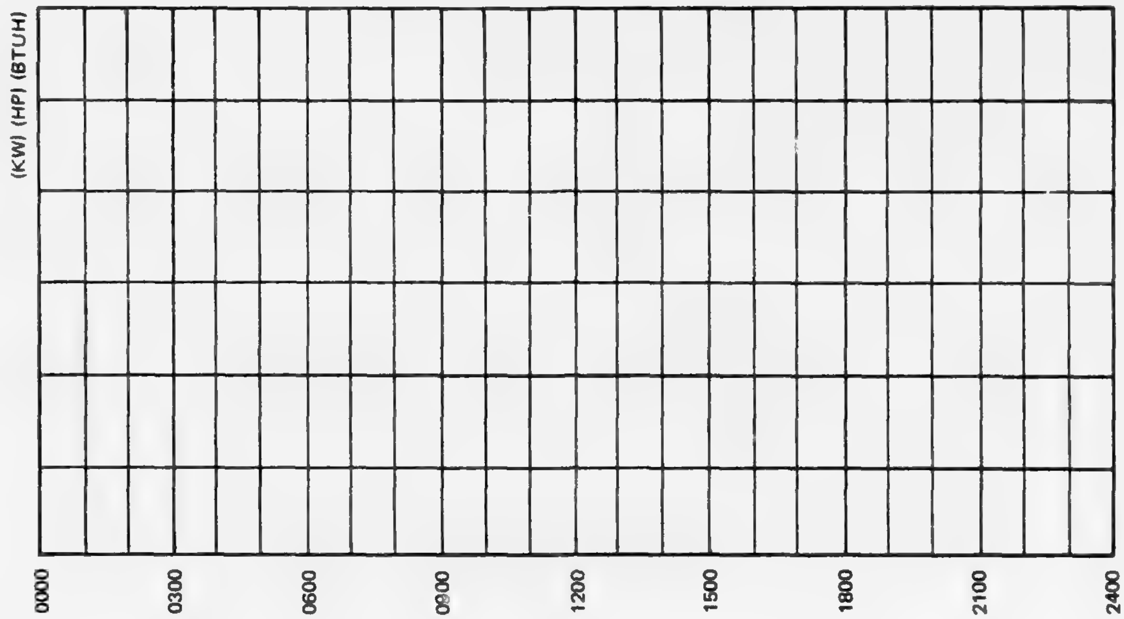
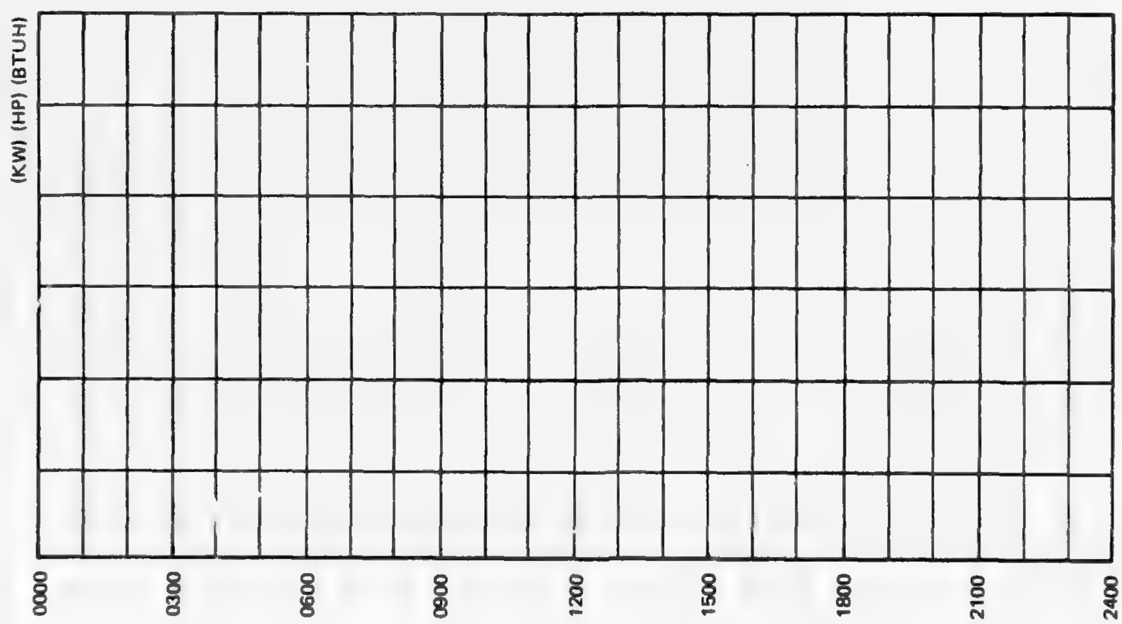
Worksheet D/1
Page 2

At peak winter thermal load



At minimum yearly thermal load -



From Worksheet A/5, determine the effect on purchased power charges of subtracting the electrical load of the candidate heat recovery plants from the overall facility load.

2. <u>Total Energy/Selective Energy Choice</u>

Does a suitable electric power network exist with which a selective energy plant can be connected electrically?

___ Yes

___ No

DECISION. If "No,"

☐ A selective energy configuration cannot be used; go to D/4. Otherwise,

☐ Continue.

Worksheet D/3
Page 1

3. Selective Energy Plant Thermal Capacity

___ of ___ (Use separate worksheet for each candidate user facility.)

____________________ Candidate User Facility Identification

List the following information on the thermal loads of the candidate user facility. Exclude peaks of short duration from maximum loads.

	Weekday			Weekend			Other		
	Min Btu/hr	Max Btu/hr	Avg Btu	Min Btu/hr	Max Btu/hr	Avg Btu	Min Btu/hr	Max Btu/hr	Avg Btu
Jan									
Feb									
Mar									
Apr									
May									
Jun									
Jul									
Aug									
Sep									
Oct									
Nov									
Dec									

DECISION. (From D/2 and D/3)

Recoverable heat capacity of prime movers, without heat storage ________ Btu/hr

Recoverable heat capacity of prime movers, with heat storage ________ Btu/hr

Will heat storage significantly improve or degrade the time relation of selective energy plant generation to network power? What will be the quantitative effect?

4. Total Energy Plant Electrical Capacity

___ of ___ (Use separate worksheet for each candidate user facility. Use only if total energy configuration is applicable.)

____________________ Facility identification

Additional capacity needed to accommodate future growth of facility or other factors. (Consider adding additional equipment at a later date.)

Reserve capacity required to ensure reliability (Depends on level of reliability required and on prime mover sizes. See Worksheet D/5.)

Consider:

___ Operating engines at overload

___ Rapid replacement of gas turbines

Potential for load shedding:

DECISION. Range of electrical capacities (state conditions):

5. <u>Selection of Prime Mover Types</u>

Consider:

___ Reciprocating Engines

  ___ Diesel

  ___ Gas

  ___ Dual Fuel

  Thermal factors:

    ___ 2-/4- cycle

    ___ Coolant temperatures

    ___ Speed/power output

    ___ Turbocharging

___ Gas Turbines

  ___ Oil

  ___ Gas

  ___ Dual Fuel

___ Backpressure Steam Turbines

  ___ Oil

  ___ Coal

Worksheet D/5
Page 2

___ Combinations of Types

Consider:

___ Gas turbines for peak loads

___ Combined cycles

___ Gas turbine exhaust to boost boilers

___ Exploitation of interruptible gas rates

___ Other

DECISION. Type(s) of prime movers suitable for application:

Worksheet D/6
Page 1

6. Selection of Prime Mover Sizes

Consider:

___ Standby requirements

___ Load shedding potential of facility

___ Reliable overload capability of engine, generator, and auxiliary equipment

___ Partial load shaft output characteristics (specific fuel consumption)

___ Partial load thermal characteristics

___ Range of common minimum daily loads

___ Avoiding frequent startup and shutdown

___ Use of dissimilar sizes

___ In selective energy systems, complete shutdown of prime movers during offpeak/low load hours

DECISION. Size(s) of prime movers, by type and number of each:

7. Selection of Heat Recovery Methods

Consider:

- ___ Steam turbine plants
  - ___ Backpressure steam heat recovery
- ___ Gas turbine plants
  - ___ Exhaust heat recovery
- ___ Reciprocating engine plants
  - ___ Exhaust heat recovery
  - ___ Jacket coolant, normal temperatures
  - ___ Jacket coolant, elevated temperatures
  - ___ Jacket coolant, ebullient heat recovery
  - ___ Combined ebullient and exhaust heat recovery
  - ___ Lube oil heat recovery
  - ___ Aftercooler heat recovery
  - ___ Radiation (equipment room) heat recovery
  - ___ Other combinations (specify):

DECISION. Heat recovery method(s) applicable, by type of prime mover:

8. Related Techniques

Consider:

- ___ Heat Storage
- ___ Heat Pumps
- ___ Clutch drives
- ___ Combinations of above
- ___ Other

DECISION. (Summary for Series D) Applicable system configurations (include user system equipment to the extent needed to indicate quantity and conditions of energy flow in overall system):

(Use extra pages, as needed.)

Worksheet E
Page 1

SERIES E - EFFICIENCY ANALYSIS*

(In most cases, the complexity of energy flows in a candidate structure is such that a computer program specifically designed for heat recovery analysis is required. The instructions accompanying such programs will indicate the manner in which information collected in the previous Worksheet Series is to be entered. The output of the computer analysis, or of other analysis methods, should be checked against the following items.)

(Attach calculations or computer output.)

Compare the following outputs for each candidate system, by month, and by hour for all day types at selected times of year:

___ Fuel consumption, for each fuel type

___ Gas demand

___ Recoverable heat used

___ Recoverable heat rejected

___ Total operating hours, each major unit

___ Operating hours by percent load, each major unit

___ Hours that heating load exceeded system capacity, and deficit

___ Hours that cooling load exceeded system capacity, and deficit

___ Total consumption of purchased electricity

___ Purchased electricity demand

Consider changes in the following factors to refine the performance of individual systems

___ Method or temperatures of heat recovery

___ Scheduling or pickup sequences of major equipment

___ Baseloading of different prime movers types (in systems with mixed types)

* Cf. Chapter 7 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

Worksheet E
Page 2

___ Equipment sizes

___ Total capacities (may strongly alter economic performance)

___ In selective energy systems, complete shutdown of engines during combined offpeak/low load hours

___ Other (specify):

DECISION. Rank candidate system configurations and baseline conventional system(s) by energy efficiency:

Worksheet F
Page 1

SERIES F - ECONOMIC ANALYSIS*

(Attach calculations or computer output.)

Consider varying the following cost factors over the range in which they may be expected to vary:

___ Initial investment

___ Salvage value

___ Life cycle duration

___ Interest rates

___ Fuel costs

___ If appropriate, vary the equipment included as part of the cost of the heat recovery systems (especially absorption chillers)

___ Consider varying cooling capacities below short duration peak/ loads

___ In selective energy systems, vary generating capacity

___ Other (specify):

DECISION. Rank candidate system configurations and baseline conventional system(s) by payback and initial investment:

* Cf. Chapter 8 of Procedures for Feasibility Analysis and Preliminary Design of Total Energy Systems at Military Facilities.

APPENDIX B: PRIME MOVER THERMAL CHARACTERISTICS

This appendix introduces the quantitative waste rejection characteristics of reciprocating engines, gas turbines, and steam turbines.

The amount of heat rejected from an engine, the distribution of waste heat between modes of heat recovery, the degree of recoverability in different recovery modes, engine life, system reliability, operational problems, and cost all change as the engine is operated under different thermal conditions. The manner in which engine thermal behavior varies with changes in individual operating conditions tends to be similar for engines in each of the three classes. These relationships will be illustrated by specific examples, which will elucidate the significance of thermal data acquired from manufacturers and will aid the engineer in requesting the appropriate information needed to develop heat recovery system configurations. The examples given are intended for illustrative purposes only, and are not valid for use in design. In all cases, data should be acquired for the specific engine model to be used.

Reciprocating Engine Thermal Characteristics

The thermal parameters of interest in heat recovery from reciprocating engines are the balance of heat between the different modes of heat rejection and exhaust temperature. The behavior of these parameters varies significantly as a function of the following options available to the designer:

1. Two-stroke or four-stroke cycle

2. Combustion cycle

3. Jacket coolant temperature

4. Engine speed

5. Aspiration

6. Engine size.

These options are listed in approximate order of their effect on heat rejection behavior.

Heat Balance

Figures B1(a) and B1(b) illustrate the heat balance of a typical engine operating with ebullient heat recovery, in absolute units and as a fraction of fuel energy input, respectively. The effect on heat balance of the design options listed above is discussed and illustrated in the following paragraphs:

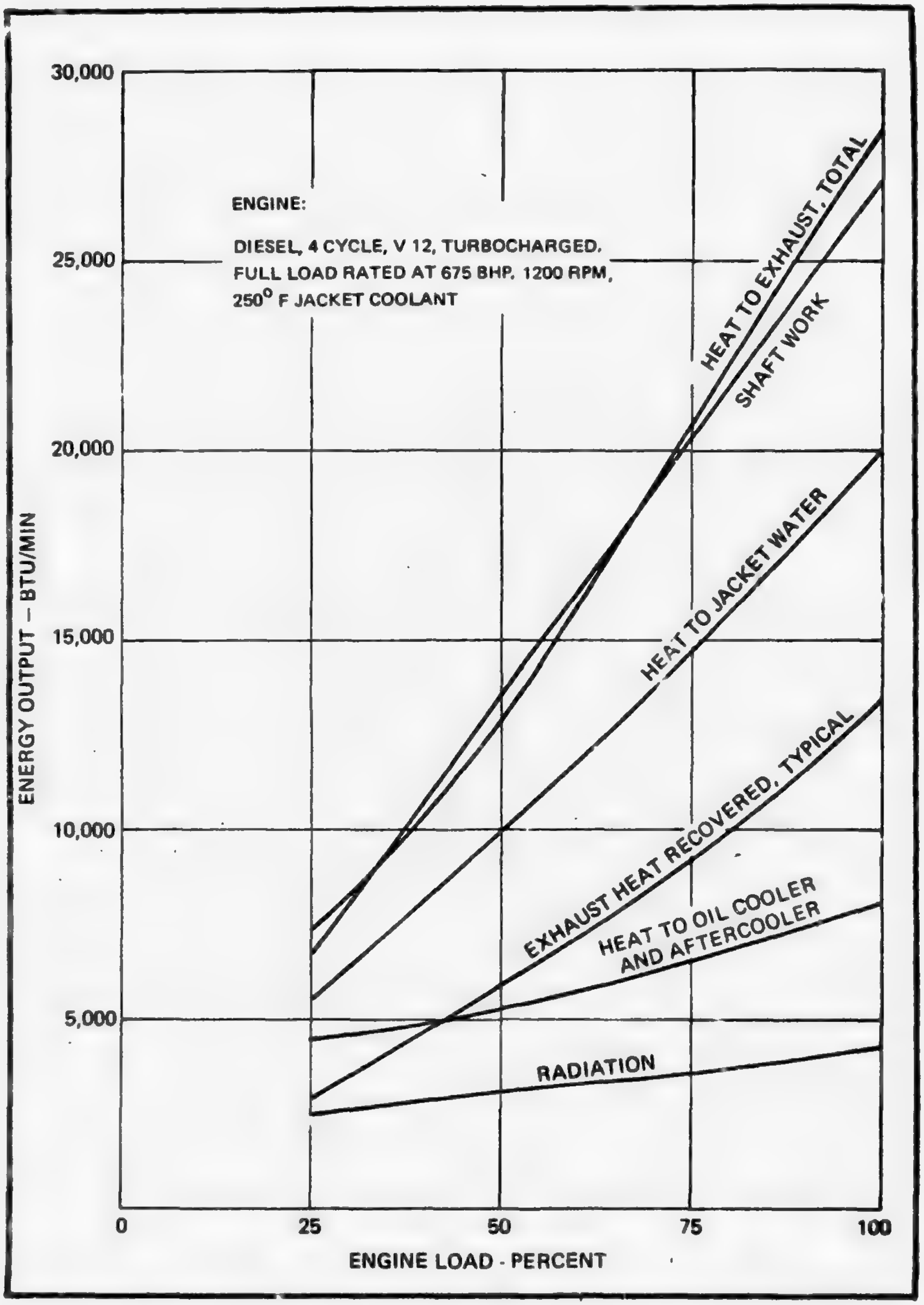


Figure B1(a). Heat balance for diesel engine in heat recovery application, absolute output.

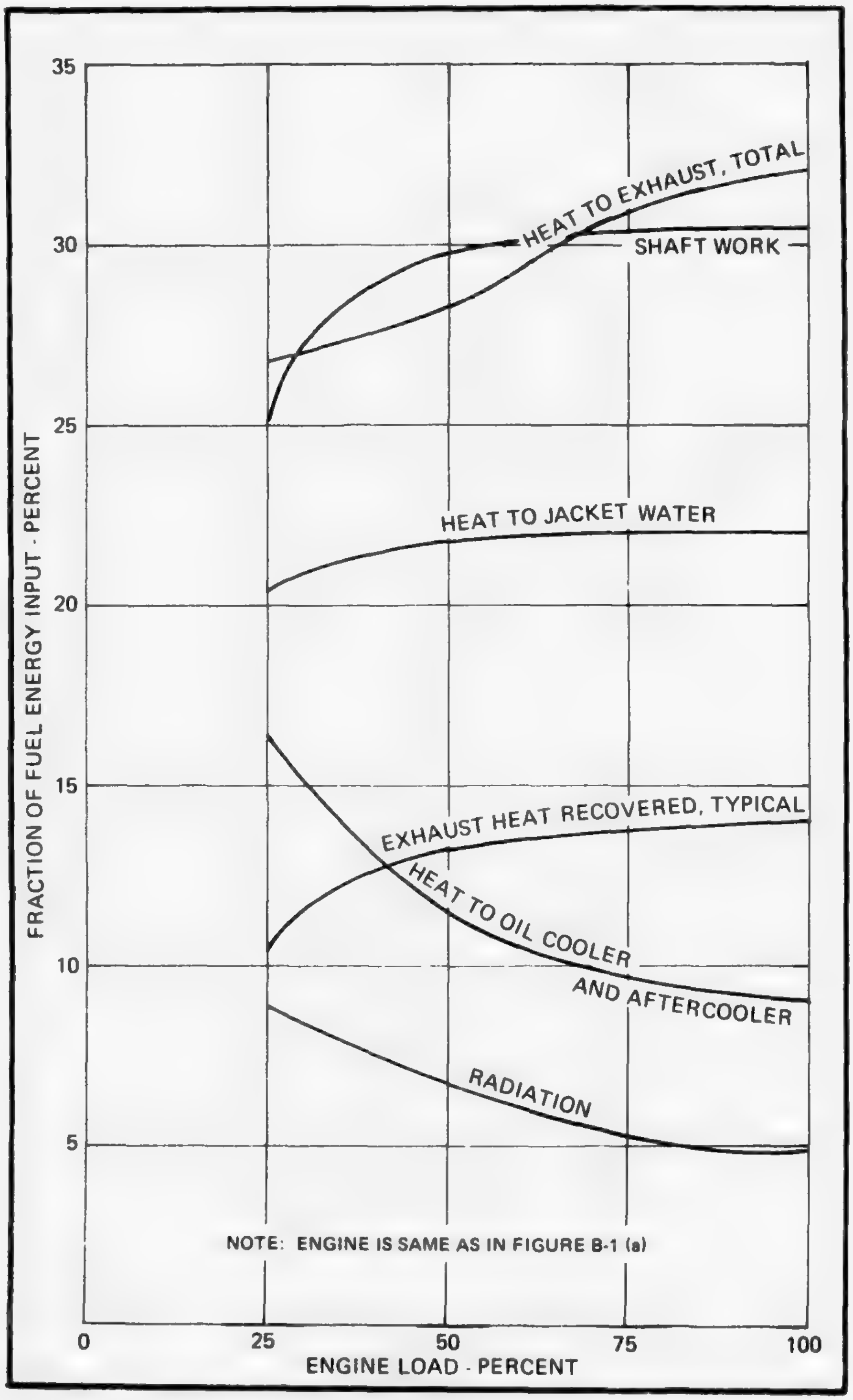


Figure B1(b). Heat balance for diesel engine in heat recovery application, relative output.

Two-Stroke vs. Four-Stroke Cycles

Figure B2 shows the heat balance diagram of an opposed piston two-cycle diesel engine superimposed on the heat balance of the four-cycle diesel engine presented in Figure B1. Both engines are similar in power, heat recovery technique, and specific fuel consumption. The large differences in the heat balance result mainly from the excess air needed for scavenging in the two-cycle engine. The increased airflow and resulting lower exhaust temperatures increase the removal of heat by the exhaust gases. The reduced cylinder temperatures in turn result in less heat being removed by the jacket coolant. Other variables being constant, two-cycle engines tend to reject more heat through the lube oil, because all strokes are power strokes. The difference between lube oil heats indicated in Figure B1 is, however, unusually large, because the two-cycle engine in this case is an opposed piston design.

Combustion Cycle

Figure B3 compares the heat balance of an oil-fueled, diesel-cycle engine with the heat balance of a gas-fueled, Otto-cycle engine. The differences are due mainly to the inherent efficiency difference of the two cycles and to the different combustion characteristics of the fuels.

Jacket Coolant Temperature

In general, raising jacket coolant temperature will reduce rejection of heat to the coolant. Thus, the use of ebullient jacket water heat recovery, which requires raising jacket temperatures to about 250°F (120°C) has the paradoxical effect of reducing the heat available from jacket coolant. Figure B4 compares the heat balances of a two-cycle opposed piston diesel engine at jacket water temperature of 165°F and 250°F (73° and 120°C), respectively. The most important feature shown in Figure B4 is that the heat which is no longer carried away by the jacket water at higher temperatures is carried away by the lube oil, along with a smaller increase in the exhaust flow. If the temperature of the jacket coolant is raised for any reason, engine operation accounts for corresponding changes in aftercooler and oil cooler temperatures if these equipments are part of the jacket coolant circuit. A significant increase in the jacket temperature of an engine above the original design value must be carried out with extreme caution; engine modification will be required in such cases.

Engine Speed

Increasing the speed of a reciprocating engine for a given power output increases heat rejection via exhaust gases, jacket

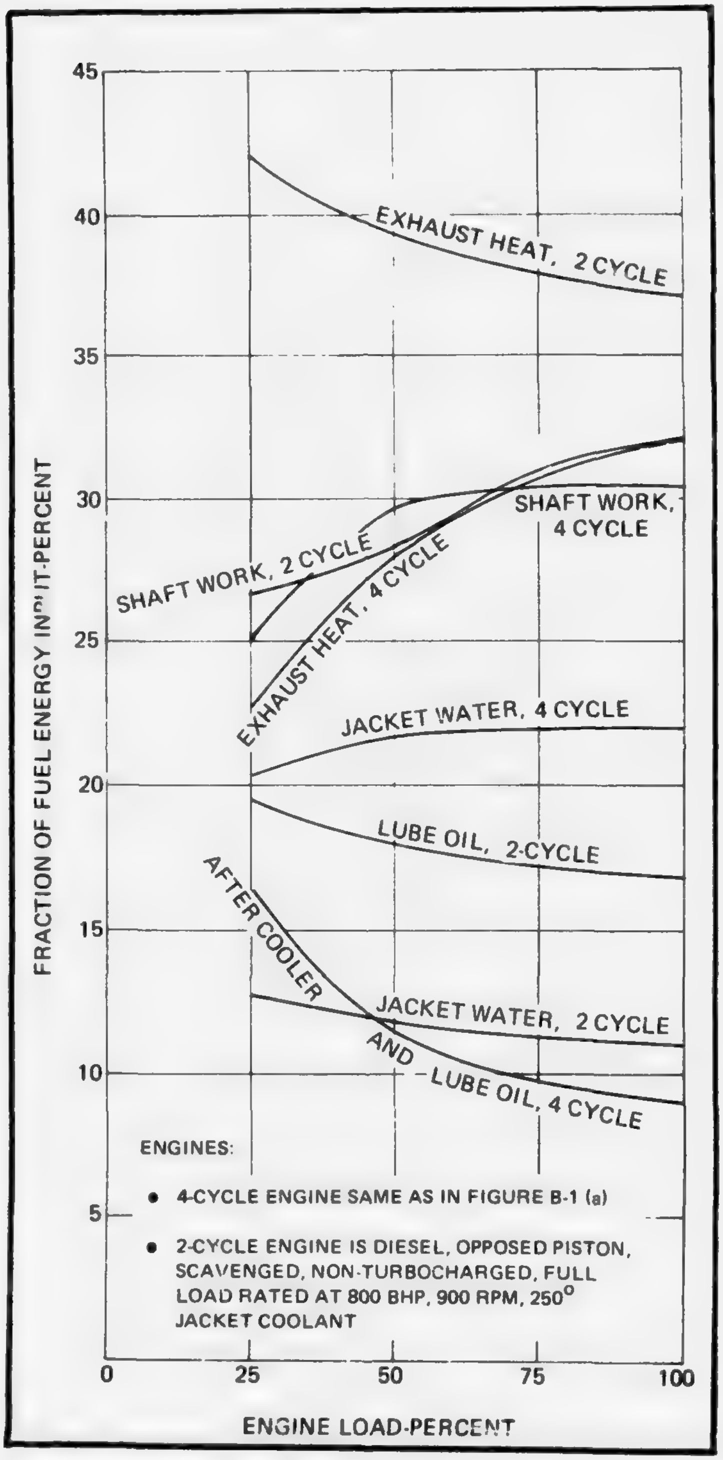


Figure B2. Comparative heat balances of two-cycle engine and four-cycle engine.

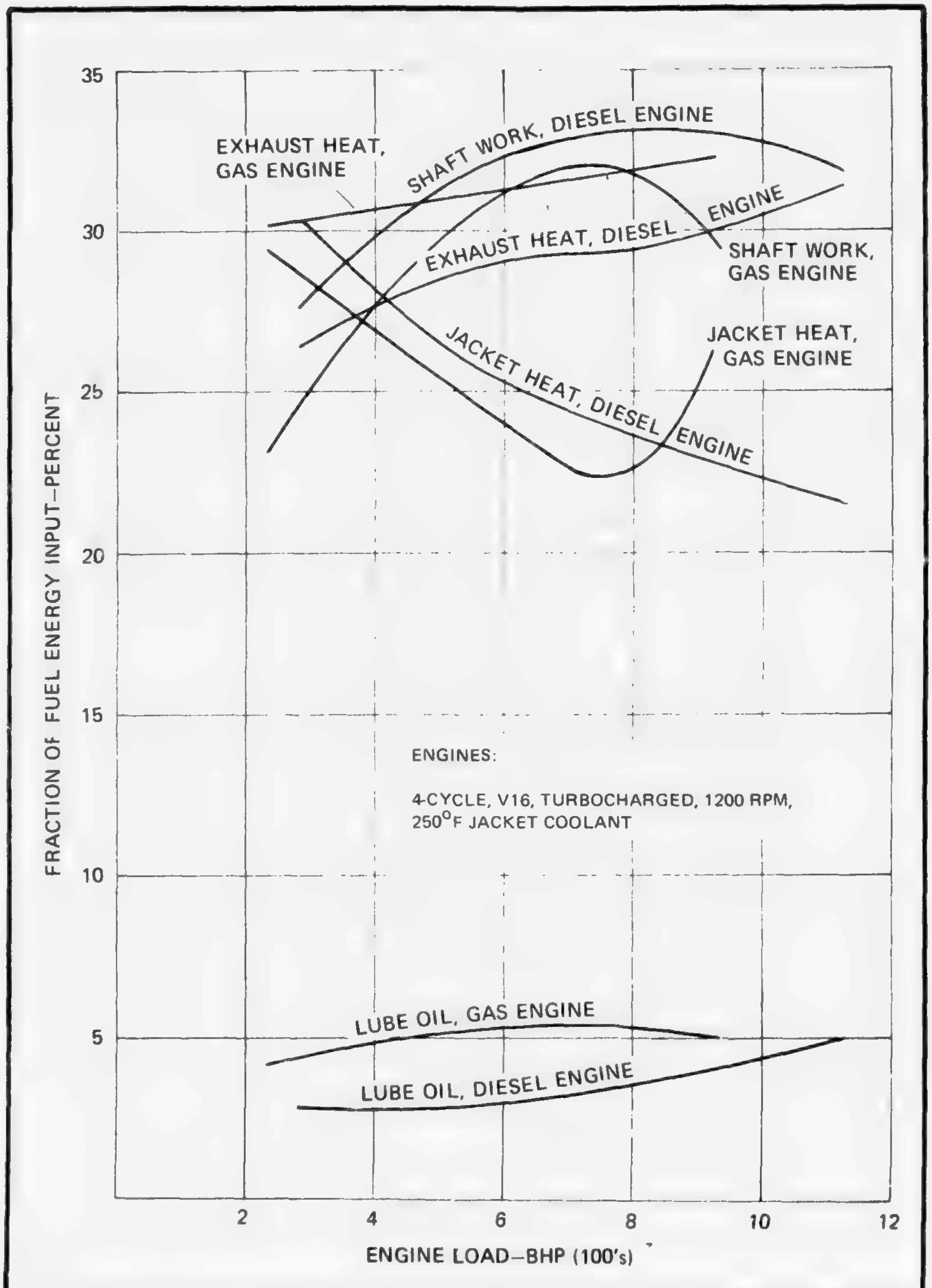


Figure B3. Comparative heat balances of diesel engine and spark-ignited gas engine.

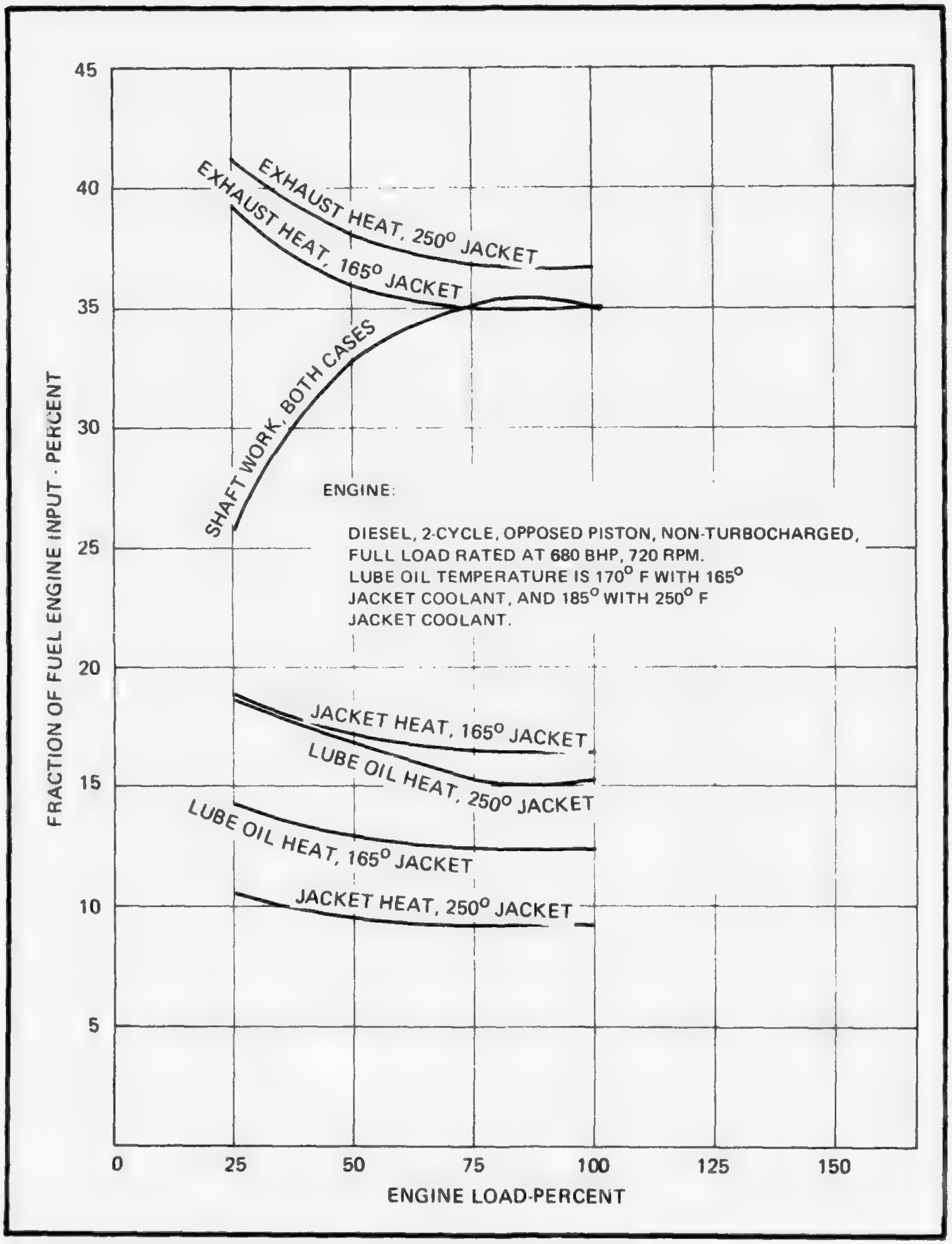


Figure B4. Effect of jacket temperature on heat balance.

coolant, and lube oil. For a given fuel energy input, these increases are all at the expense of shaft output. Figure B5 compares the heat balances of a two-cycle opposed piston engine operated at two different speeds, as a function of absolute power output. In continuously operated engine plants, the principal consideration in selecting design speed should be engine life, which can be enhanced considerably by operating at reduced speed.

Aspiration

The addition of a turbocharger to an engine substantially increases power output, and usually reduces specific fuel consumption under higher loads. Typically, a significant reduction occurs in the rejection of heat through jacket coolant and lube oil, while a greater relative amount of heat is lost through exhaust and radiation, and into the added aftercooler. In many engines, the aftercooler is included in the jacket coolant circuit, so that the reduced rejection of heat to the jacket is partially balanced by the added aftercooler heat. Figure B6 shows the effect on heat balance of adding a turbocharger to a large, two-cycle, opposed piston diesel engine.

Engine Size

Engine size has only a minor effect on heat balance. Smaller engines are generally somewhat less efficient in producing shaft work, and reject somewhat more heat through jacket coolant and radiation. Figure B7 compares the heat balances of a 250-hp engine and a similar 1000-hp engine. The principal discriminant between large and small engines in continuous duty is that larger engines characteristically have longer intervals between major maintenance.

Exhaust Temperature

The extent to which exhaust heat is recoverable from an engine is a function of the absolute amount of heat available in the gases, which is a function of the engine heat balance and of the exhaust temperature. Different engine types vary widely in their exhaust temperature characteristics. In the design of a heat recovery system, the effect of the following six factors on exhaust temperature should be taken into account.

Two-Stroke vs. Four-Stroke Cycles

In general, the exhaust temperatures for a two-cycle engine tend to be much lower than for a four-cycle engine, due to the excess air which is carried in the two-cycle engine for scavenging.

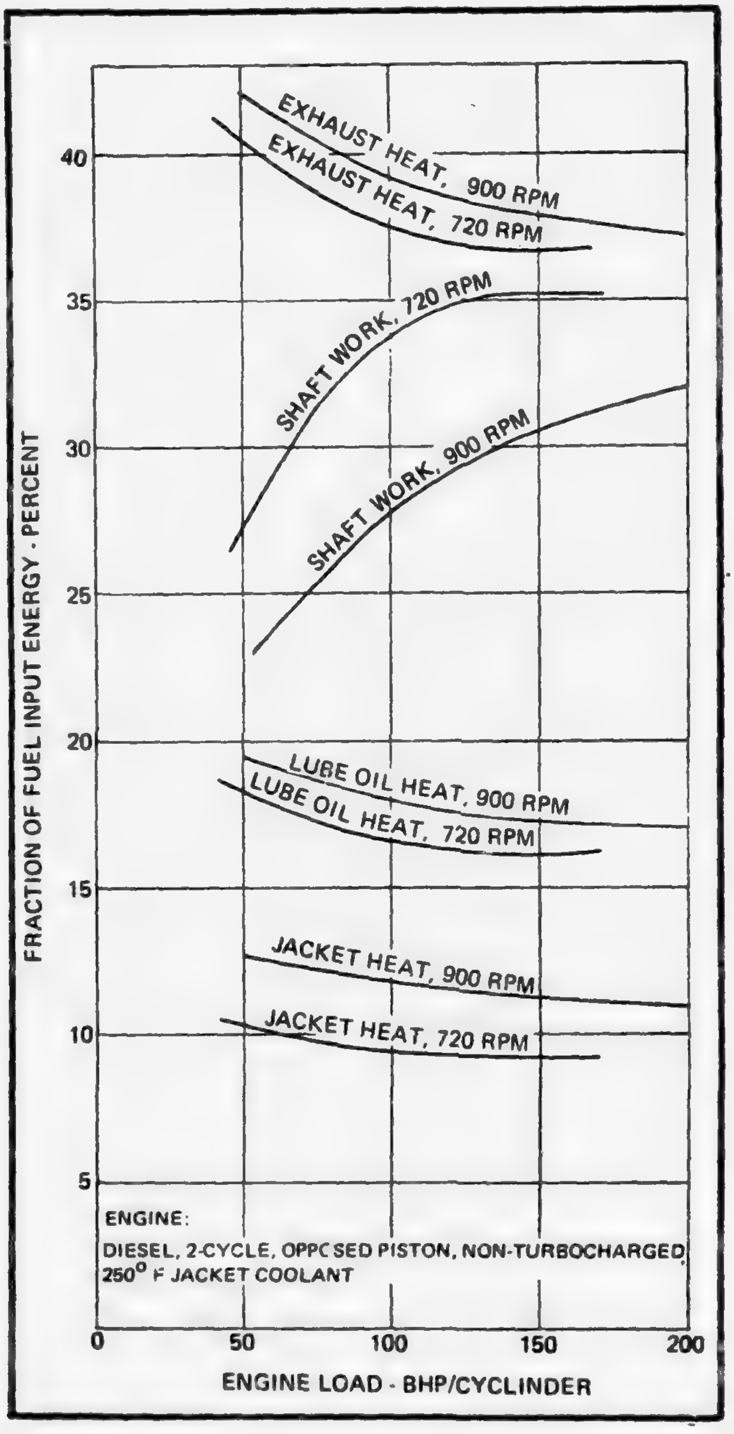


Figure B5. Effect of engine speed on heat balance.

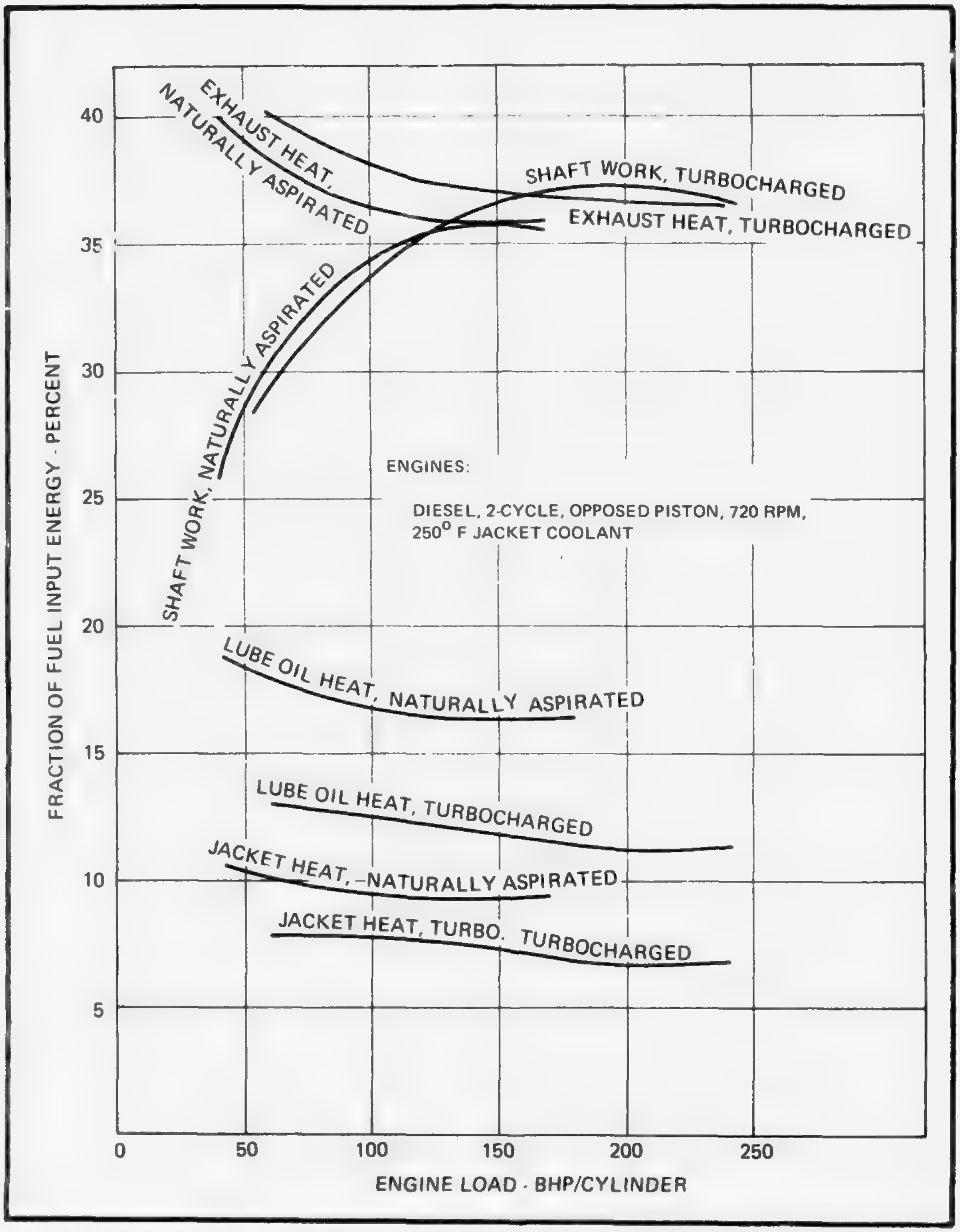


Figure B6. Effect of turbocharging on heat balance.

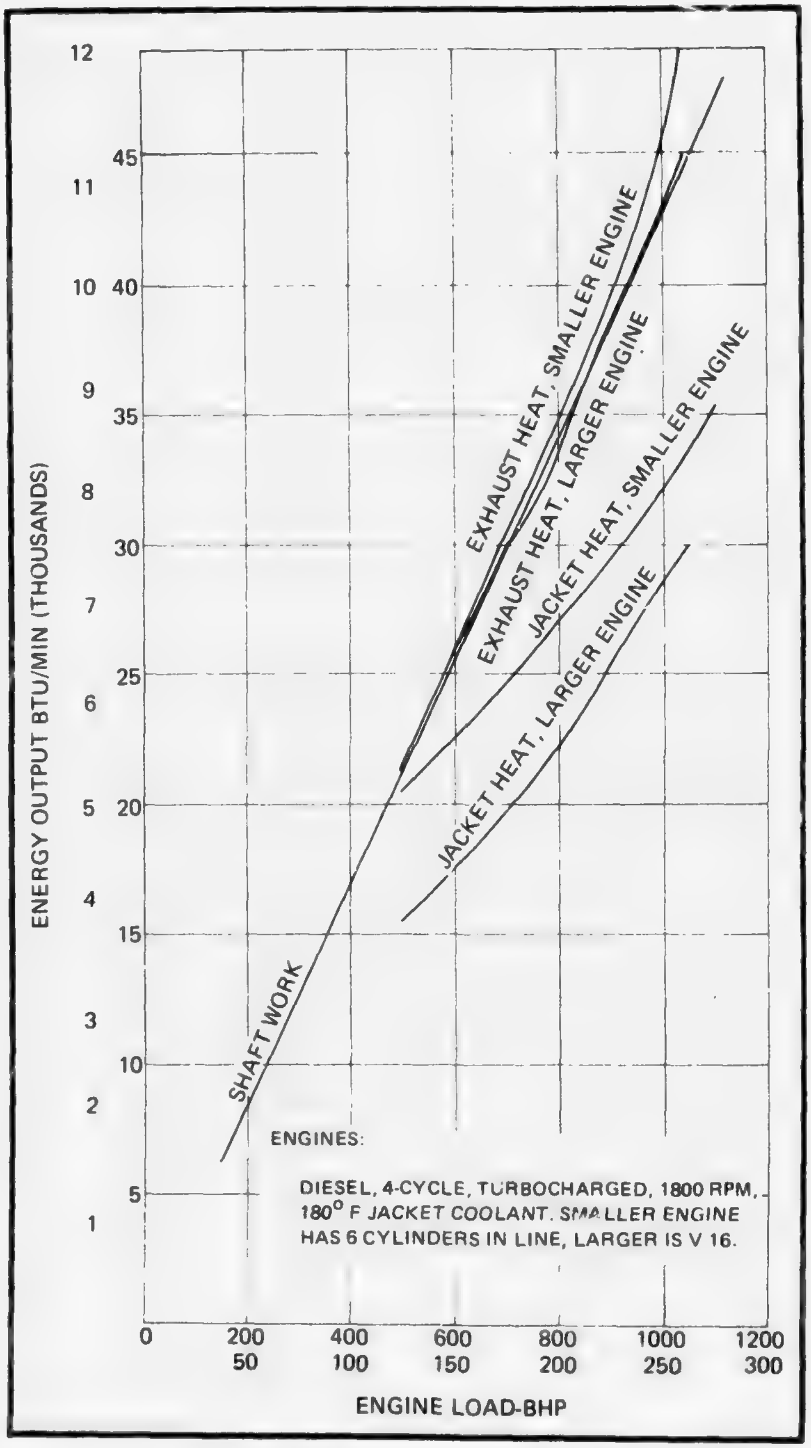


Figure B7. Effect of engine size on heat balance.

With two-cycle engines operating at low loads, exhaust heat recovery is particularly problematic because the temperature drop across the heat exchanger is reduced severely at part loads. With two-cycle diesel engines at low loads, the exhaust temperature is little higher than the 300°F (147°C) minimum outlet temperature which is advisable with conventional heat exchangers made of corrodible materials. Figure B8 compares the exhaust temperatures of conventional four-cycle and two-cycle diesel engines.

Combustion Cycle

Spark-ignited, gas-fueled engines have much higher exhaust temperatures than diesel engines, due to (1) the greater efficiency of the diesel cycle compared to the Otto cycle, and (2) the differences in the fuel characteristics. Diesel engines operating at low loads will be severely limited in exhaust heat recovery. Figure B9 compares the exhaust temperatures of a spark-ignited gas engine and a diesel engine.

Jacket Coolant Temperature

Raising the jacket coolant temperature causes a small rise in exhaust temperatures, generally of less than 50°F (10°C) in all engine types. More significant is the fact that varying the jacket coolant temperature causes the exhaust temperature to vary in the same direction as the exhaust heat content, so that exhaust heat recovery is always increased by raising the jacket temperature.

Engine Speed

Increasing engine speed also increases exhaust temperature. (See Figure B10). Since exhaust heat also increases with engine speed, greater heat recovery is always achievable at higher engine speeds.

Aspiration

The temperature of the exhaust from a turbocharged engine is determined by the exhaust turbine inlet temperature and the amount of heat removed from the exhaust by the turbine. In many conventional engines, stack temperature is changed little by turbocharging (see Figure B11). However, this is largely coincidental; thermodynamic data from an engine with one type of aspiration should not be assumed to be similar to one with different aspiration.

Engine Size

Exhaust temperature does not change significantly as a function of engine size alone.

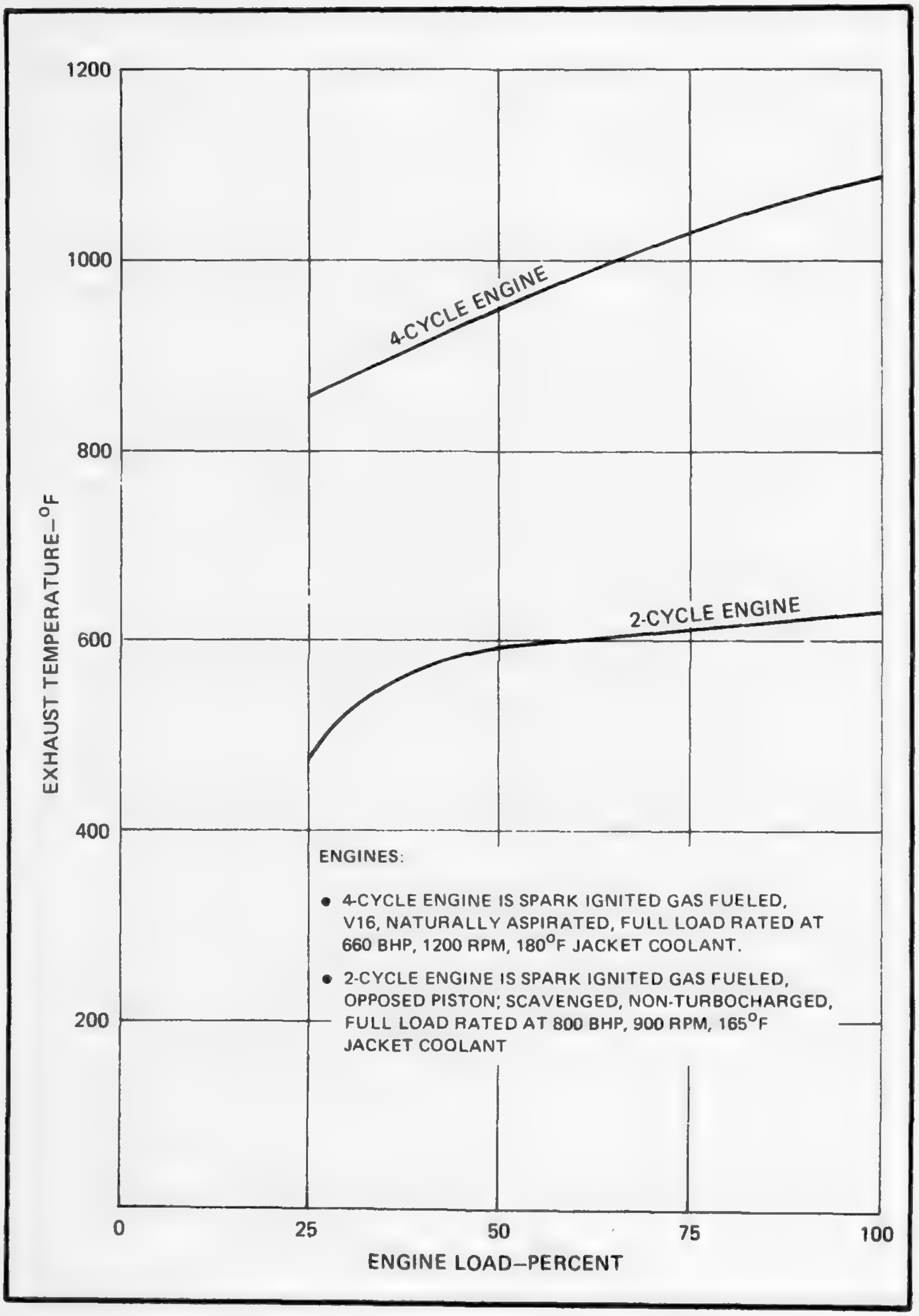


Figure B8. Comparative exhaust temperatures of two-cycle and four-cycle engines.

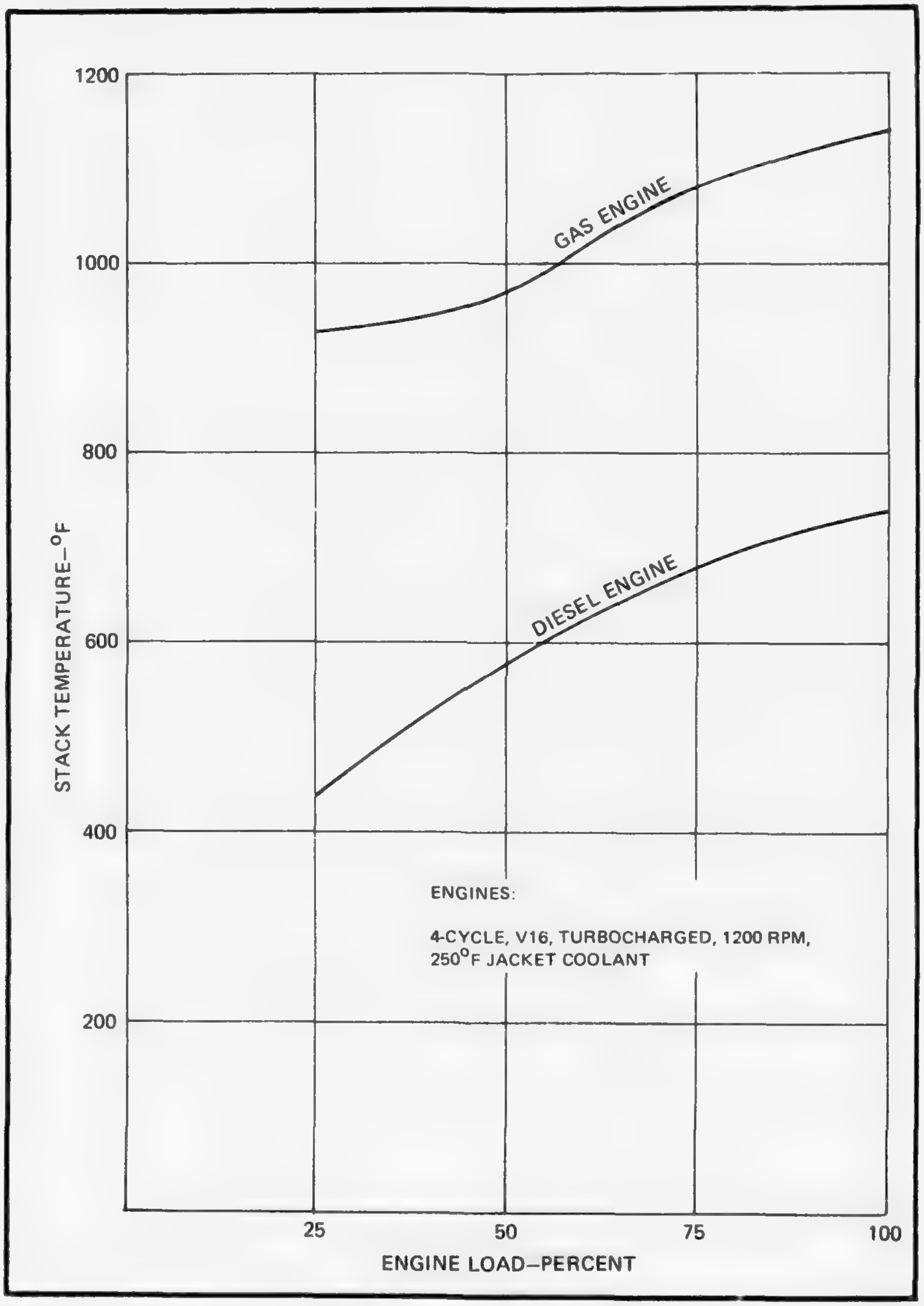


Figure B9. Comparative exhaust temperatures of diesel engine and spark-ignited gas engine.

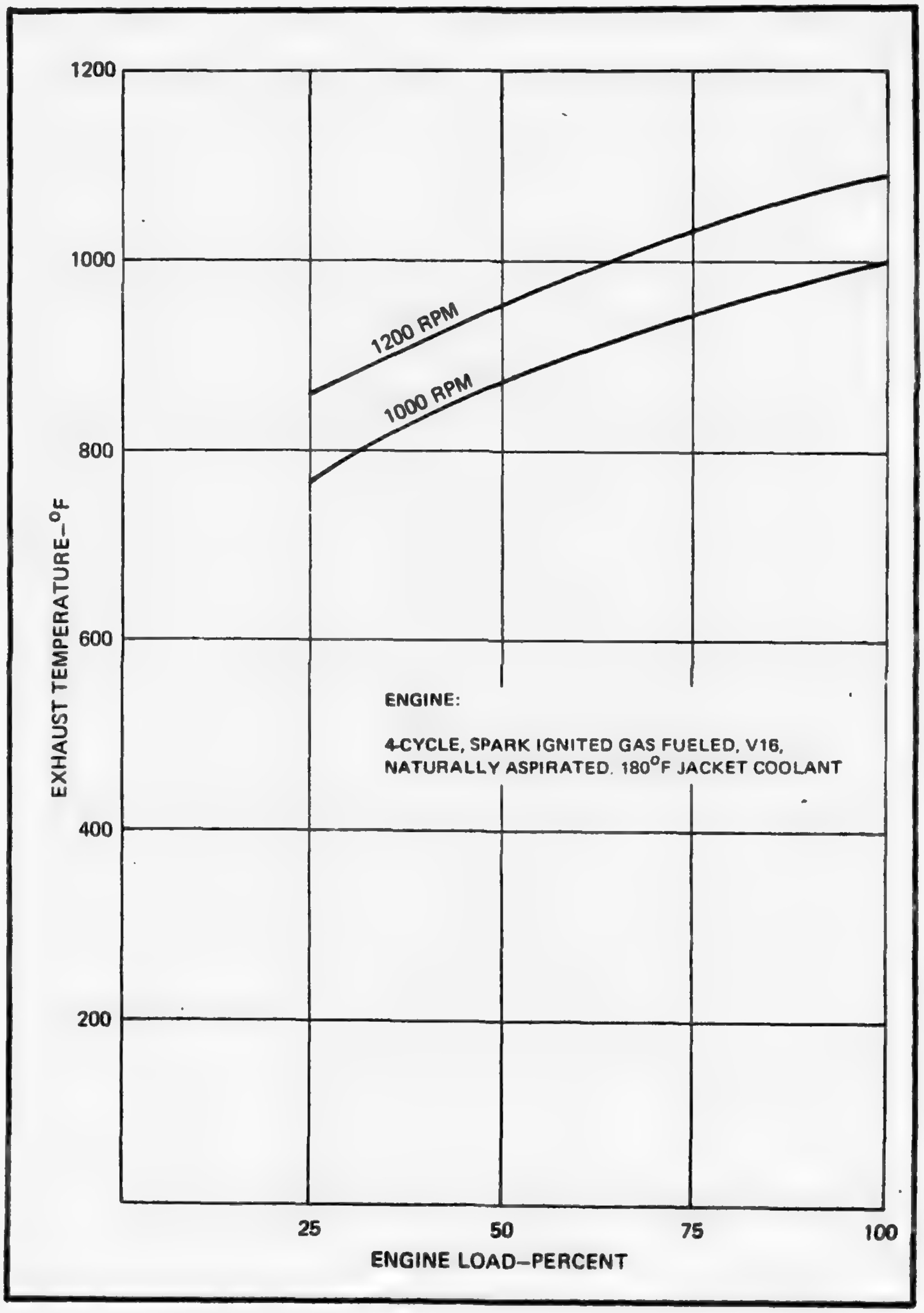


Figure B10. Effect of engine speed on exhaust temperature.

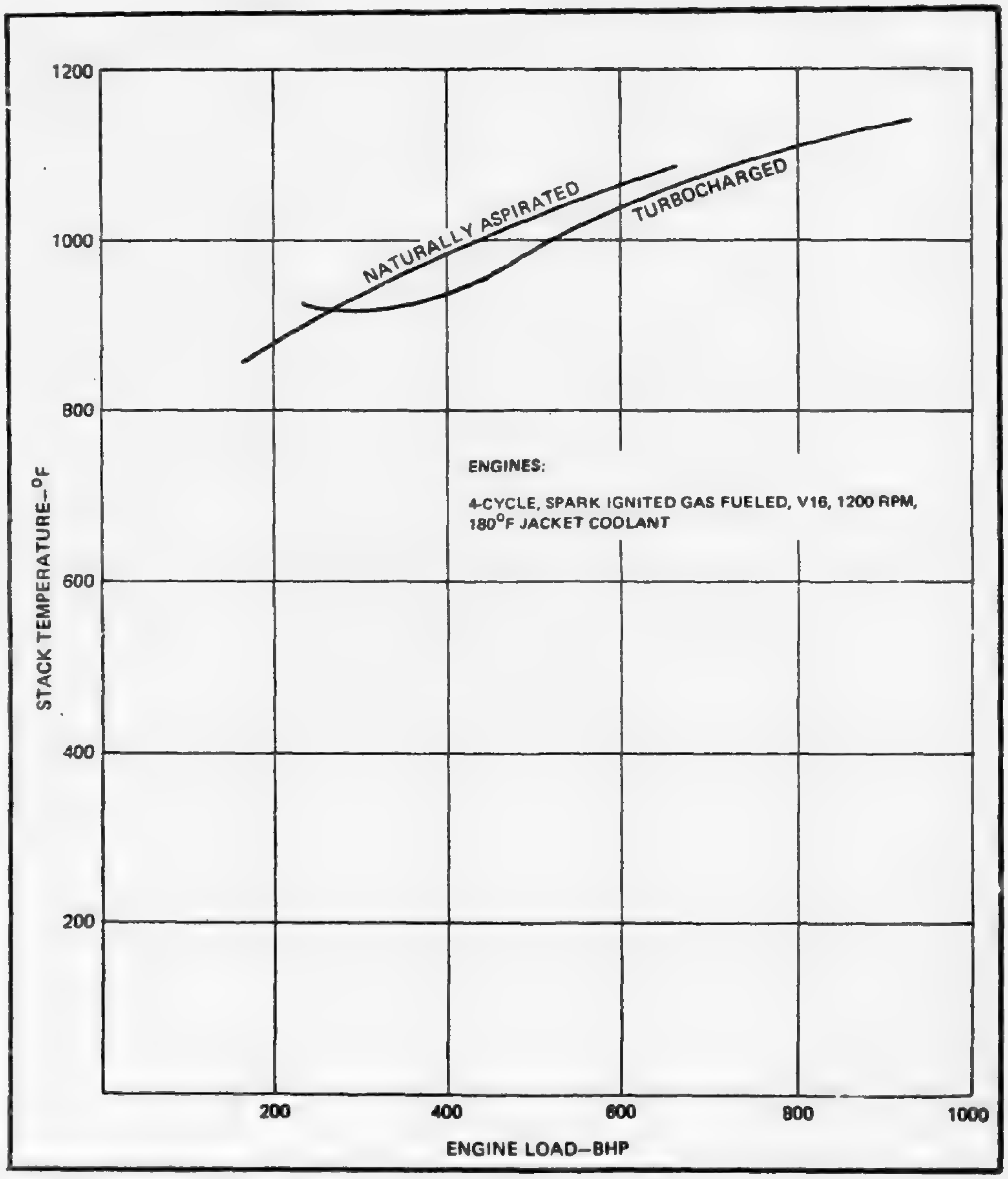


Figure B11. Effect of turbocharging on exhaust temperature.

Gas Turbine Heat Characteristics

The most important thermal characteristics in heat recovery from a gas turbine are the balance between shaft output and exhaust heat, and the temperature of the exhaust. Analyzing these factors for heat recovery purposes is much simpler for gas turbines than for reciprocating engines.

Heat Balance

Regarding the recovery of waste heat, the principal gas turbine thermal characteristics are (1) the relatively high proportion of input energy which is rejected as heat (at the expense of shaft efficiency), and (2) the concentration of all significant amounts of recoverable heat in the exhaust gases. The sensitivity of gas turbine shaft output to inlet and exhaust duct losses, inlet air temperature, and altitude is documented in manufacturers' data and standard references. Variation in air inlet temperature has a marked effect on both exhaust gas flow and exhaust volume--factors which determine exhaust heat recovery. In most conventional gas turbines, the effect of these two factors on heat balance tends to be that each cancels the other; thus, large differences in inlet temperature do not strongly affect the balance between shaft work and exhaust heat. However, this cannot be assumed for all gas turbines, since substantial differences in thermal characteristics are caused by the many variations in gas turbine design. Several gas turbine designs now being developed exhibit thermal characteristics significantly different from those of present gas turbines; these will require additional detailed heat recovery analysis when they become sufficiently ready for utilities use. Figure B12 gives the heat balance for a typical 1100-hp industrial gas turbine.

Exhaust Temperature

The exhaust temperature of conventional open-cycle gas turbines remains relatively high at partial loads. Exhaust temperatures are lower overall for larger, more efficient turbines. With any given gas turbine, exhaust temperature changes significantly with air inlet temperature changes. Figure B13 shows exhaust temperature at two different inlet temperatures for a common gas turbine.

Steam Turbine Heat Characteristics

Condensing steam turbines do not produce waste heat at temperatures useful for conventional applications, because the nature of water as a working fluid dictates that the temperature of heat

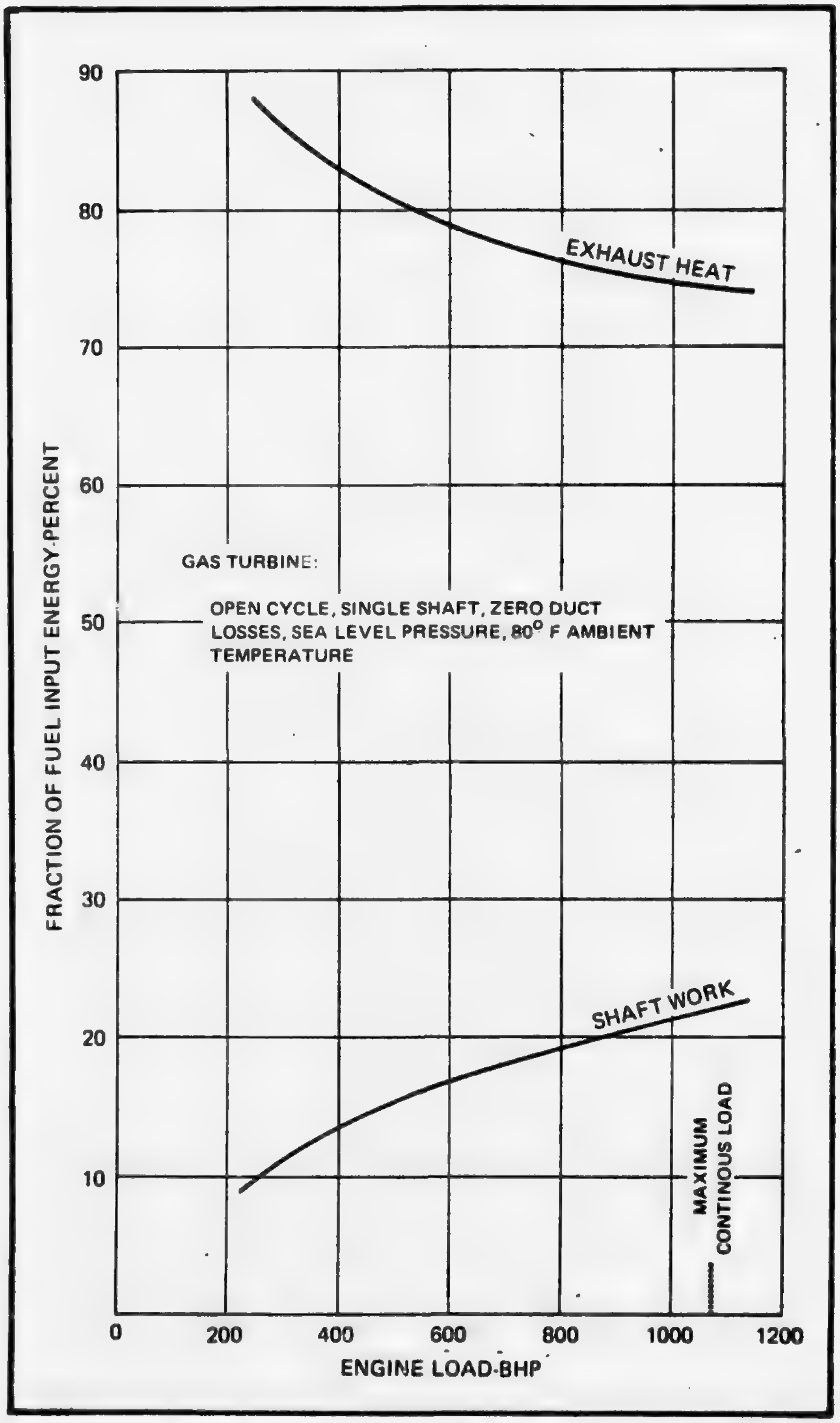


Figure B12. Gas turbine heat balance.

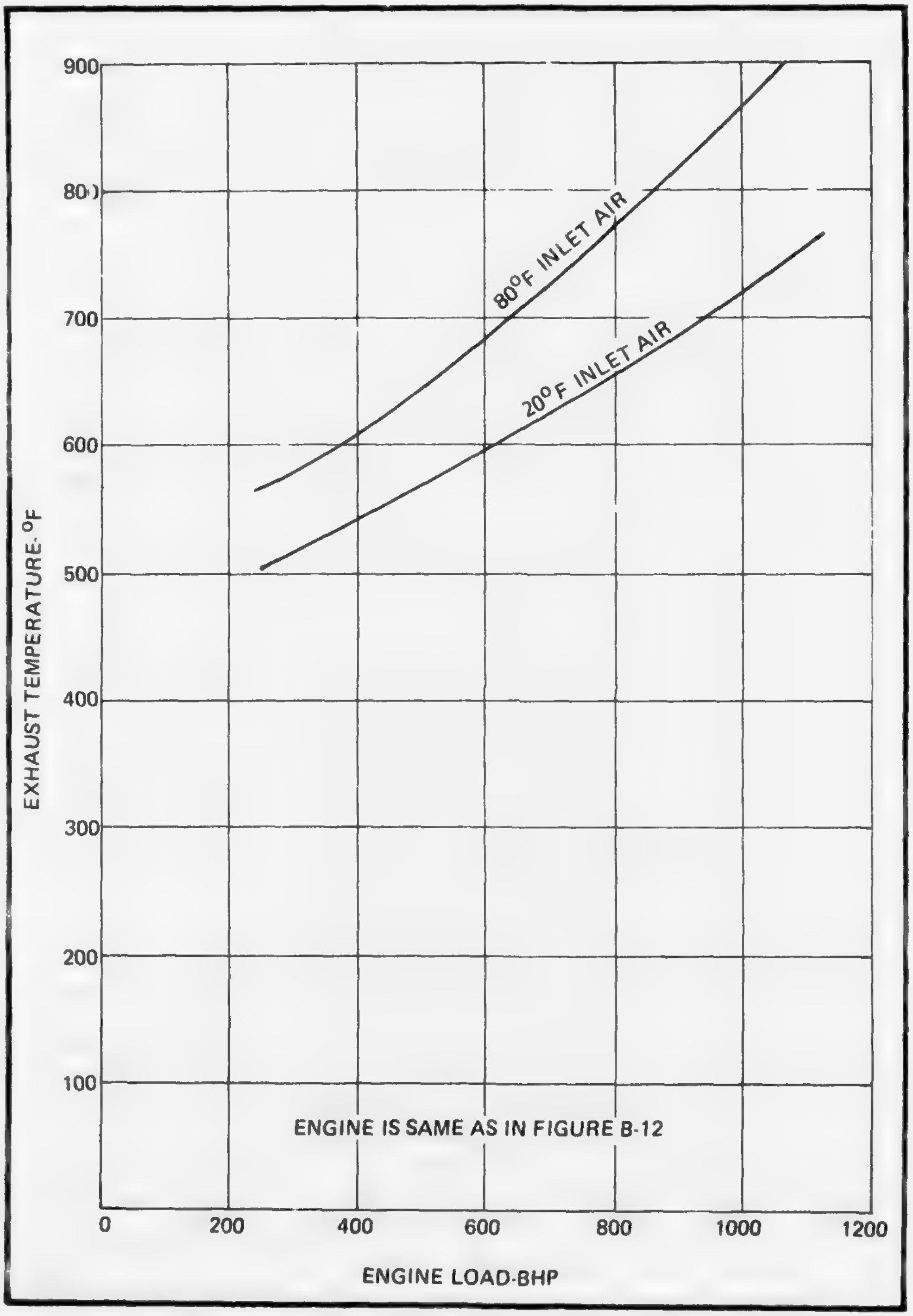


Figure B13. Effect of inlet air temperature on gas turbine exhaust temperature.

rejected from the condenser be nearly ambient. Hence, any heat recovered from a steam cycle will be at the expense of shaft output. Recovery of heat at useful temperatures can be accomplished by exhausting steam at elevated pressures into a user line. However, the operation of turbines with outlet pressures appropriate to common heat recovery applications severely reduces turbine shaft power.

Figure B14 shows the relative fuel requirements of a fixed extraction (backpressure) steam turbine and a variable extraction steam turbine, respectively, compared to conventional utilities. The thermodynamic features of steam power design can be found in standard references.

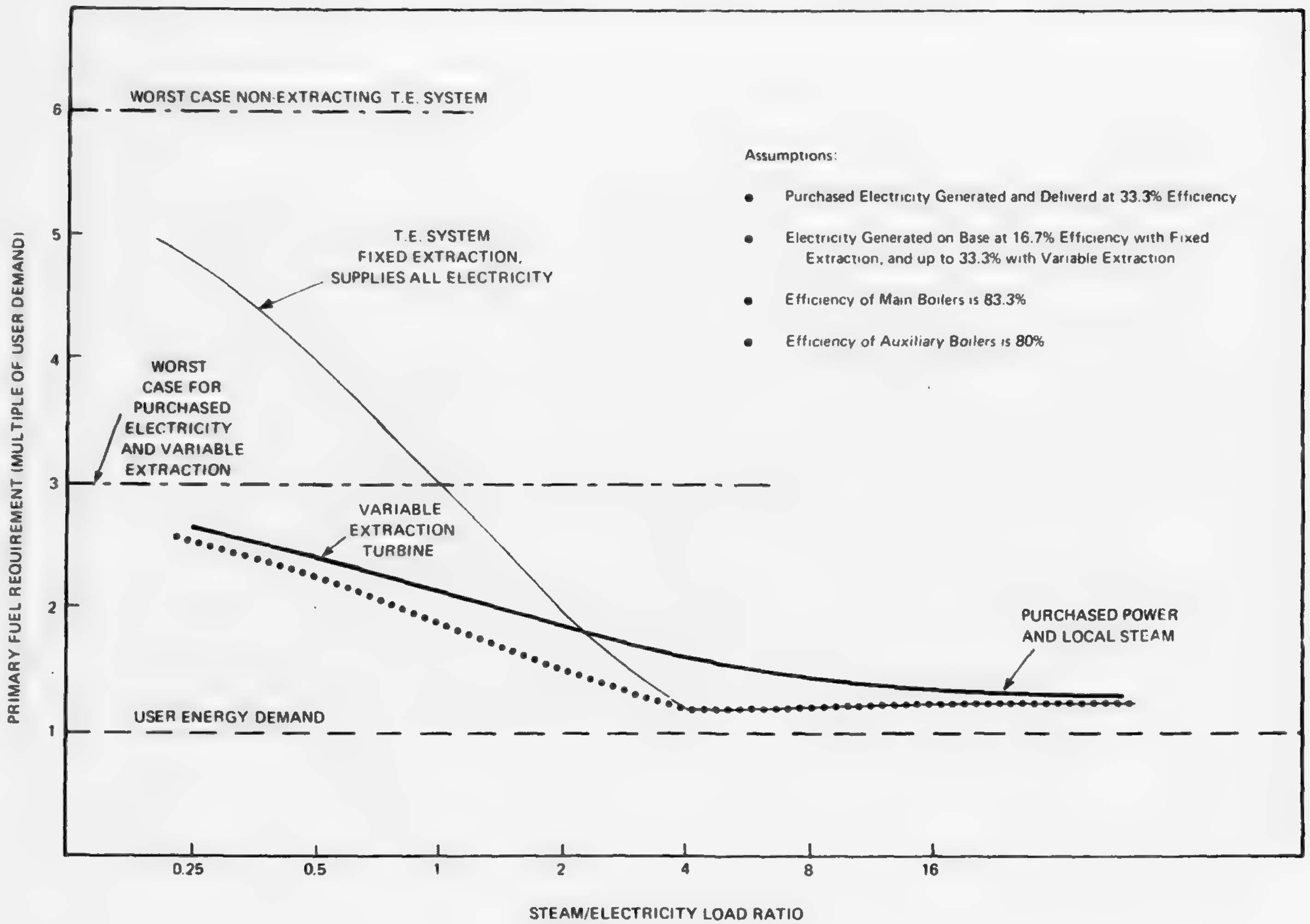


Figure B14. Primary fuel energy required to satisfy unit energy requirement with conventional utilities and with steam turbine heat recovery systems.

APPENDIX C: GENERAL GUIDELINES FOR DEVELOPING HEAT RECOVERY SYSTEM CONFIGURATIONS

The aspect of heat recovery system feasibility analysis which is least subject to systematic approach is the development of specific equipment configurations. Discussions of the various factors to be considered in developing equipment configurations were presented in Chapter 6. However, the actual application of these factors is largely a matter of engineering judgment, familiarity with the specific candidate sites in question, and knowledge of constantly changing equipment characteristics. The following collection of miscellaneous configuration guidelines is for the engineer who must apply principles from Chapter 6 to develop a family of candidate configurations from which an optimum configuration can be selected using the detailed methods described in Chapter 7. These guidelines are based on experience with specific systems and on the state of the art at the time of this writing. They are neither comprehensive nor universally applicable, and should be tempered by the user's judgment.

With typical load profiles, the energy efficiency and cost effectiveness of the TE/SE system itself decreases with increasing size. The total potential for energy savings increases with size up to a point beyond which it remains constant. Overall cost effectiveness is maximum at some intermediate size. The optimum plant size should be estimated with graphs of energy input and cost to provide unit energy demand. Systems sized over a range surrounding the estimated optimum point should be given detailed evaluation.

Operating a facility around the clock pays off the capital investment faster. Energy load "seesaw" between buildings helps keep load high, but not necessarily balanced. However, "seesaw" may help balance if heat/cold storage is used.

A TE configuration should be used at sites where security of the entire facility load is critical, and where it is not possible to interconnect with an external power network. In all other cases suitable for TE, an SE configuration should also be considered.

Consider a selective energy configuration at sites where the overall load is so small that no more than one or two prime movers can be used efficiently, and where the night load is inadequate to provide efficient load to even a single engine. In other words, use selective energy for smaller facilities which do not operate continuously.

At noncritical facilities, consider an SE configuration to reduce or eliminate equipment costs for reserve capacity.

At facilities with a critical load, consider an SE configuration if shedding of the noncritical load can be accomplished.

Consider increasing the size of an SE configuration to shave the demand peaks of a larger facility electrical system.

Make the generating capacity of selective energy plants large enough to cover the critical load, thereby eliminating the need for idle emergency generators.

Provide input heat for absorption chilling only from engine waste heat, because fuel-fired absorption cooling is energetically less efficient than large compression chillers. Boilers should be used for chiller input only if they provide a small fraction of yearly chiller input heat. If more cooling is needed than can be supplied by absorption chillers operated with waste heat, use compression chillers driven by the prime movers either directly or electrically.

The balance between shaft load and heat output during cooling conditions can be increased efficiently by using prime mover driven compression chillers or by using electric motor driven compression units with electricity provided by the TE/SE prime movers.

Electric motor driven chillers provide somewhat less system efficiency than direct prime mover driven units because of electrical conversion losses, and require higher capital cost for motors and generators. However, they have greater flexibility because the chillers do not depend on a single engine and may be located remotely.

In steam turbine heat recovery systems providing steam at pressures above approximately 100 psi, consider the use of double-effect absorption chillers, which require 30 to 40 percent less energy input than single-effect units, at approximately 40 percent higher equipment cost per ton.

Use only waste heat resulting from necessary (e.g., electricity) or efficient (e.g., heat pump) shaft loads. Do not load engines (e.g., with resistance heaters) to generate extra heat, because the engines then act as high maintenance/low efficiency boilers. Use conventional fuel-fired boilers for additional heat.

The balance between shaft load and heat output can be improved by using heat storage. With current technology, heat storage can be effective for several days.

If water heat storage is used, storage temperature should be as high as possible to reduce the storage volume required.

Radiation heat from the engines can be recovered by using the engine room as an air source for a heat pump or for a makeup air run-around loop.

Waste heat boilers with overfiring capability should be considered for installations where the heat load cannot be entirely supplied by waste heat.

In installations where waste heat is recovered at more than one temperature, size the user loads so than an excess of waste heat will first appear in the higher temperature system, allowing the excess heat to be diverted to the lower temperature system.

In heating systems with variable operating temperatures (e.g., in perimeter zone radiators controlled by ambient temperature), use heat storage tanks as a temperature buffer between the engines and the heating system.

In terms of primary fuel consumption, heat pumps driven (either directly or electrically) by engines from which heat can be recovered are the most efficient available means of heating. Heat pumps should be considered for heating whenever they can sufficiently justify their capital cost.

When heat pumps are employed, the entire heat recovery system must be designed to be compatible with the relatively low temperatures efficiently attainable from heat pumps, or alternatively, separate high and low temperature heating systems must be used.

If substantial heating and cooling loads frequently occur on the same day (e.g., as occurs with any form of reheating HVAC system), heat pumps should be configured to provide both heating and cooling. Daily phase variations in the heating and cooling loads should be compensated with heat storage.

Keep the system as simple as possible, consistent with efficient operation and easy maintenance.

Avoid nonstandard or exotic components.

Provide sufficient instrumentation so that the plant's operating efficiency can be readily determined, and so that a malfunction at any point in the system can be located directly.

If the heat load is low during most of the year, engine shaft efficiency becomes the predominant factor in the system's overall efficiency. In such cases, it is especially important to acquire engines with greatest shaft efficiency.

Examine the user load profile and select engine sizes so that engines on line will remain near peak loading with a minimum of engine startup and shutdown.

Two-cycle engines have much lower exhaust temperatures than four-cycle engines, and the exhaust temperature drops drastically with reduction in load. Also, a smaller fraction of waste heat is recoverable from jacket water in two-cycle engines. Hence, unless the high lube oil heat rejection of two-cycle engines can be exploited, they are significantly less favorable for heat recovery than four-cycle engines.

The best use of gas turbines is in applications where the thermal load remains at least approximately twice as high as the shaft load. For backpressure steam turbines, the thermal load should remain about three times greater than the shaft load. Reciprocating engines are the best choice where thermal loads are low, and may be best for all except very large thermal loads.

Engine loading should be conservative, especially for ebulliently cooled reciprocating engines. Spark-ignited, natural-gas reciprocating engines may generally be operated near their normal continuous rated load. Diesel engines should be derated to substantially less than their normal rated loads.

In applications where a reciprocating engine will be used with ebullient or high-temperature jackets, specific engine models should be specified which have been proven in this type of service, and procurement should be restricted to the models used in the design configuration.

Maintenance factors, such as rapid replacement of certain gas turbines, and availability of spare parts and factory service, should be treated as major factors in model selection.

In steam turbine heat recovery systems, caution should be exercised when selecting the type of steam turbine to be used. In extraction turbines, as opposed to straight backpressure turbines, shaft efficiency may vary considerably with different extraction conditions.

In applications where a selective energy system may be used and where the night load is very low compared to the day load, consider sizing the engines to the day load and shutting down the engines when the load is too low for them to run efficiently.

For satisfactory shaft efficiency, gas turbines should be employed only in applications where they may operate near full load most of the time. Diesel plants should be sized to carry primary loads to 60 to 100 percent of derated full load, but single-engine night loads may be substantially lower. Reciprocating natural gas engines should not drop below approximately 60 percent load. Steam turbine system efficiency is relatively insensitive to variation in load.

The distribution of engine sizes in a multiple engine installation should be based on the load profile. If the load is always a large fraction of the peak load, high engine loading can be maintained with few engines. If there are long periods during which the facility load becomes a small fraction of peak load, at least one engine should be small enough to remain moderately heavily loaded at all times.

In total energy systems, consider reducing capital cost by using gas turbines to add peaking or reserve capacity to base-loaded reciprocating engines. If the peaks are of short duration, the overall reduction of fuel efficiency may be small.

Consider using waste heat recovered from reciprocating engines and gas turbines to preheat feedwater.

Consider using exhaust from gas turbines, which contains approximately 18 percent oxygen, as preheated combustion air in boilers.

Idle reciprocating engines, except those purely on standby, should be kept warm by circulating jacket coolant from running engines through them. In a selective energy plant where the engine or engines are shut down during off-peak hours, warm water from a boiler, heat storage, or domestic storage should be available for circulation through the engines for a period subsequent to daily shutdown and prior to daily startup.

Except where a running reserve is needed, a minimum number of engines should be operated.

All running engines should be run at equal loading, except that it may be advantageous to remove all load from an engine on running reserve. Smaller engines should carry single-engine loads, and should be dropped when larger engines are needed.

Water treatment should be rigorous in installations with ebullient cooling, where scale formation and oxidation of coolant passages can become a serious problem. In other modes of operation, especially at elevated jacket temperatures, jacket water should be demineralized and corrosion inhibitors should be used.

If existing engines are to be converted to heat recovery operation, be wary of converting to ebullient cooling. Engines operated with conventional cooling may not be suitable for ebullient cooling, and at a minimum will require major parts changes. Engines that have been operated with conventional cooling for long periods may have excessive accumulations of scale and sludge in the water jackets, thus reducing heat transfer and making ebullient cooling hazardous.

Exhaust gas heat exchanges or boilers must maintain a temperature of at least 212°F (100°C) at all points on the exhaust side, to prevent

corrosive condensation. If the temperature of the waterside is more than 212°F (100°C), condensation cannot occur (assuming adequate external insulation) and heat exchangers can be sizes as large as is desired for maximum heat transfer. If the waterside temperature is not above 212°F (100°C), the heat exchanger must be sized small enough so that part load operation does not allow exhaust outlet temperatures to drop below 212°F (100°C).

Operational problems with heat recovery equipment and engines will be minimized if the exhausts from different engines are not allowed to enter common passages. It is advisable either to use a separate heat recovery boiler for each engine, or to use boilers having separate tube rows and flues for each engine.

The use of high-temperature jacket water should be considered as an alternative to ebullient cooling as a means of using jacket heat to drive absorption chillers. In installations using this method, larger chiller sizes must be used to achieve a given cooling capacity.

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